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Psychological Monographs: General and Applied

Effects of Light on Electrical Excitation of the Human Eye[1]

Lorrin A. Riggs, Janet C. Cornsweet,[2] and Warren G. Lewis[3]

Brown University

Theories of color vision are based primarily on results of experiments on color mixture, spectral luminosity, effects of adaptation and contrast, and the wave-length discriminations of normal and color-blind subjects. These sources have yielded a large amount of information, but have failed to provide conclusive evidence on such basic matters as the number of fundamental response curves and the spectral characteristics of each.

In view of the failure of traditional approaches to the problems of color vision, it would seem desirable to follow any promising new leads that become available. Among these are the recording of gross electrical responses (electroretinograms) in the human eye when it is stimulated by lights of various wave lengths, and microelectrode studies of the responses of single retinal units in certain animal preparations. Unfortunately, the spectral sensitivity data obtained by Granit (7, 8) and others by microelectrode techniques of recording have not in the first place involved the human eye, and in the second place they have been based on somewhat indirect calculations. This follows inevitably from the fact that recording was from third-order neurons, each of which was activated by a combination of numerous receptor cells. The human electroretinogram is even more a reflection of mass electrical activity; and while it has yielded some evidence for individual color response processes, it is far from a direct measure of the spectral characteristics of each.

The Motokawa Experiments

A new and different method of relating retinal phenomena to problems of color vision has recently been described by Motokawa (16, 17, 18, 19). This method is one in which the human eye is stimulated briefly by an electric current, using silver electrodes in contact with the skin of the brow and cheek. Currents of a few tenths of a milliampere are sufficient to stimulate the retina. They give rise to "phosphenes," which present an appearance to the subject (*S*) of vaguely defined clouds of light in the peripheral field of view. An electrical threshold is determined by reducing the current in successive presentations of the test pulse until the *S* reports that the phosphene is no longer aroused. The electrical threshold so determined is found to be influenced by the state of adaptation of the eye and by other variables. Of particular interest to Motokawa is the observation that a flash of light, occurring before the electrical pulse is delivered, acts to increase the sensitivity of the eye to electrical stimula-

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tion. This suggests that the electrical threshold can be used as a measure of the excitability of the eye, so that the effects of light on the eye may be evaluated by measuring the alterations that the light produces in the electrical threshold. Specifically, Motokawa has undertaken a series of studies in which a flash of light has been followed at a given interval by a test pulse of direct current. A threshold is determined for the stimulating current, on the basis of its ability to arouse phosphenes in the stimulated eye. A comparison is made between the phosphene threshold following a light and the phosphene threshold in the dark. In this way a measure is obtained for the enhancement of the phosphenes by the preceding light. Since Gebhard (6) has reviewed these papers by Motokawa, no attempt is made here to give a complete account of them.

Of primary interest in Motokawa's work is the time course of the enhancement following lights of various colors. Figure 1 shows this time course for white, green, blue, and red lights. The ordinate is the zeta-value, Motokawa's measure of enhancement, where

$$\zeta = \frac{E - E_0}{E} \times 100$$

In this expression E is the momentary excitability or reciprocal of electrical threshold at some particular time after the flash of light, and E_0 is the reciprocal of an electrical threshold determined by delivering test pulses during a portion of the experiment in which no light is present. The abscissa is the delay time, i.e., the interval of time between the cessation of the flash and the onset of the electrical test pulse. In these experiments, the duration of the light is 2 sec. and the duration of the test pulse is 0.1 sec. It will be noted that ζ rises steeply immediately following the flash

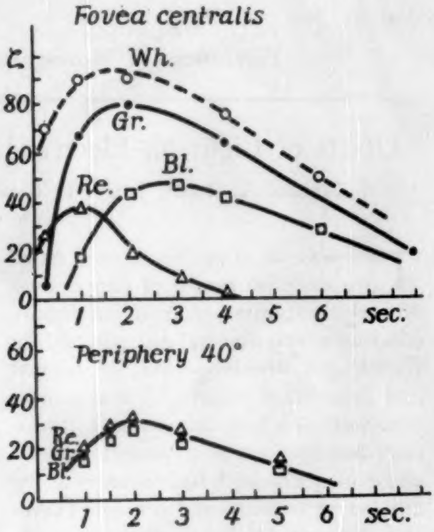


FIG. 1. Curves obtained by Motokawa (16) for the electrical excitability of the human eye as functions of time after flashes of light. Two-second flashes of red, green, blue, and white light were used with a 2° field centrally fixated (upper graph) and in the periphery (lower graph). The ordinate is the zeta-value as described in the text. These results of Motokawa are to be compared with Figures 6 and 9 of the present series of experiments.

of light. Thereafter, each function reaches a maximum at a delay time that is characteristic of the *color* of the preceding light. Motokawa reports that these "crest times" are highly stable at approximately 1 sec. for red, 2 sec. for green, and 3 sec. for blue light. The absolute size of ζ is related to the intensity of the light and varies somewhat from one S to another, but the shapes of the functions are said to be highly reliable and the crest time for each wave length exhibits little variation from one experiment to another. Hence Motokawa concludes that his method has revealed the specific temporal aftereffects of light in the three fundamental receptor systems for color in accordance with the trichromatic theory.

Further support for the trichromatic theory is given by many later experiments reported by Motokawa. The most fundamental of these is one in which spectral lights were used to pre-expose the eye. The results are shown in Fig. 2. Again the ordinate is ζ, the measure of relative enhancement of electrical threshold by the pre-exposure to light. This time, however, the letters *R*, *G*, and *B* are not used to represent red, green, and blue lights as they did in Fig. 1. Instead, the letter *R* is used to designate a function relating enhancement, ζ, to the wave length of the light flash under conditions in which there is a delay time of 1 sec. between the flash and the test pulse. A similar function for a delay time of 2 sec. is labeled *G*, and the third function, for a delay time of 3 sec., is labeled *B*. These particular delay times are the "crest times," or delay time yielding maximum enhancement, obtained for red, green, and blue pre-exposing light in the previous experiment. (See Fig. 1.)

The curves are labeled *R*, *G*, and *B* in Fig. 2 because Motokawa believes that these delay time

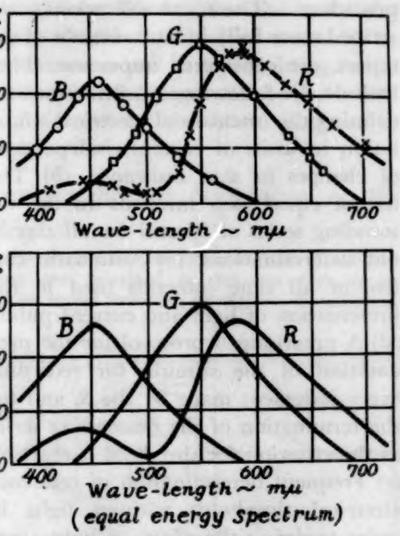


FIG. 2. Curves obtained by Motokawa (16) for the electrical excitability of the human eye as functions of wavelength of preceding flash of light. Two-second flashes, 2° central field. B, curve obtained for a 3 sec. delay time after the flash. G, curve for a 2 sec. delay time. R, curve for a 1 sec. delay time. The lower graph contains the three "physiological sensation curves" obtained by correcting the upper curves for spectral energy distribution.

curves represent the fundamental response curves for the three basic color processes. The rationale for using delay times to single out the individual color response mechanisms has not been fully explicated in the papers by Motokawa. It is claimed, however, that curves such as those in Fig. 2 "can be regarded as an expression of real physiological processes in the retina obtained by direct observations," and that they may be called "physiological sensation curves." Thus Motokawa distinguishes between them and the "fundamental sensation curves" derived from color mixture and other psychophysical data by Maxwell, Abney, Konig, Hecht, Stiles, Wright, Walters, Pitt, and others (see Wright, 25).

The seemingly direct approach that Motokawa has used is based on certain assumptions whose validity may certainly be questioned. Implicit in the use of this method is the assumption that, at a delay time of 1 sec. after the flash, the electrical sensitivity of the eye is enhanced primarily by the aftereffects of the light on the red response mechanism of the eye. It is on the basis of this assumption that the curve in Fig. 2 for a 1-sec. delay time is designated as *R*, the curve for the red response mechanism. It is similarly assumed that for the 2-sec. curve, *G*, it is the green mechanism that is predominantly involved; and for the 3-sec. curve, *B*, the blue mechanism is assumed to predominate. It is difficult to understand how these assumptions can be made, however, in view of the shapes of the curves in Fig. 1. These curves indeed exhibit maxima at approximately the times indicated for red, green, and blue light respectively. But they also indicate that (*a*) at 2 sec. the effect of red light is fully half as great as at 1 sec.; (*b*) at 2 sec. the effect of blue light is almost as great as it is at its peak of 3 sec.; and (*c*) green light is almost equally effective in producing enhancement of electrical sensitivity at delay times of 1, 2, and 3 sec. after the flash. In other words, *the curves of Fig. 1 are not so sharply peaked at the times of*

1, 2, and 3 sec. as to suggest that each of these particular times is likely to characterize exclusively the delay time of any one of the (presumptive) three fundamental response mechanisms for color.

Motokawa has taken some account of the above difficulty by assuming that the degree of enhancement at a delay time of 3 sec., for example, is not exclusively determined by aftereffects occurring within the blue response mechanism. Enhancement is greatest, and therefore the threshold for electrical stimulation is lowest, with the blue mechanism at a 3-sec. delay time. But some degree of enhancement is thought to exist within the green mechanism and also the red. Hence the concept of "multiple thresholds," which plays an important part in Motokawa's theory of enhancement. It is Motokawa's contention that the lowest, or "true" threshold is one whose value at 3 sec. delay time is fixed by the action of the blue response mechanism. Higher thresholds exist, however; and these "apparent" thresholds result from the lesser actions of the green and red mechanisms at this delay time.

In summary, the work of Motokawa and his associates has offered a new approach to the problems of human color vision. Our interest has centered on the "physiological sensation curves" that have emerged from the experiments involving direct electrical stimulation of the eye. These curves have been worked out on the basis of test pulses of direct current applied to the eye at fixed intervals following flashes of colored light. The electrical test procedure reveals that electrical sensitivity is enhanced by light, and that the time course of the enhancement is specific to the wave length being used for the flash. For the extension of these basic experiments to the topics of fatigue, form perception, etc., the reader is referred to Gebhard's comprehensive summary (6) and the original works cited therein.

The Purpose of the Present Investigation

Our main goal in undertaking these experiments has been to furnish an independent check on the basic wave-length effects reported by Motokawa and his collaborators. We have made no attempt to repeat the whole extensive series of experiments. Instead we have chosen to concentrate on the basic phenomenon underlying much of this research, namely that of specific wave-length effects in the enhancement of electrical excitability following flashes of light. We have made every effort to observe wave-length effects under varying conditions of stimulus area and intensity.

The method followed in these experiments was fundamentally that developed by Motokawa. However, we felt compelled to introduce certain modifications in the interests of standardization of the procedure. These modifications, described more fully in later sections of this report, are considered important. They include the following: (*a*) Provisions for defining the intensity of electrical stimulation in units of current, independent of changes in skin resistance. (*b*) The use of equal step intervals in the descending series of stimuli for all threshold determinations. (*c*) Automatic control of all time intervals used in the presentation of light and current pulses. (*d*) A prearranged protocol for the presentation of the stimuli, for recording every judgment made by the *S*, and for the termination of the descending series as the criterion for threshold is reached. (*e*) Frequent determination of reference electrical thresholds without light in order to define the effects of light upon the threshold. (*f*) Employment of all the obtained data rather than discarding any results on the basis of variability in reference thresholds.

These modifications were introduced with the expectation that they would serve to reduce the effects of uncontrolled variables in such experiments.

For this reason it was anticipated that the effects of light itself would be more readily apparent in the results. It is apparent, however, that the use of these modifications means that we have not repeated exactly the experiments of Motokawa. Thus any basic differences between his results and ours are perhaps attributable in part to differences in procedure. Because of our concern with procedure we have made at the outset an extensive study of the variability characteristics of the basic method used by Motokawa as compared with the conventional method of constant stimuli.

Apparatus and Procedure

In all of the experiments to be reported here, the *S* was seated in a light-tight, electrically shielded room. The experimenter was in an adjoining room. A thin partition separated the two rooms as indicated by the block diagram in Fig. 3.

Arrangements for Stimulation of the Eye

Optical system. The optical system is adapted from one described by Johnson (11) in an earlier report from this laboratory. It consists of a tungsten source, collimating lenses, neutral density and color-selective filters, a rotating disc shutter, and a final lens that focuses the light on a spot within the pupil of the *S*'s right eye. Auxiliary devices include a dull red fixation point and a diaphragm to limit the size of field. A recent attachment to the apparatus is a special eyepiece that may be inserted to extend the field diameter to 38°. This consists of a negative lens, placed between the eye and the last lens of the usual optical system, and a positive lens of short focal length used next to the eye. The negative lens renders parallel the rays emerging from the regular optical system, and the positive lens focuses them on the pupil of the eye. A bite board of dental impression wax is used to position the head of the *S* so that no part of the light is occluded by the edges of the pupil. This positioning is easily accomplished by an experienced *S*, since the rays emerging from the apparatus are brought to a focus that is smaller than the natural pupil of the eye. The *S* views the last lens of the system filled with light ("Maxwellian view"). The fixation point appears to be at the center of this lens.

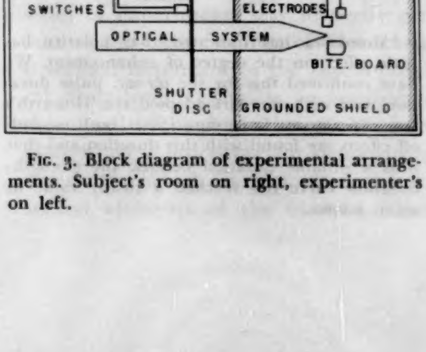


Fig. 3. Block diagram of experimental arrangements. Subject's room on right, experimenter's on left.

Calibrations of the intensities of the stimulating lights were made by the procedure outlined in an earlier report (Riggs, Berry, and Wayner, 23). By selecting appropriate filter combinations it was possible to present filtered light stimuli of various dominant wave lengths and of intensities such that they were of equal effectiveness in stimulating the eye. This equality could be achieved on the basis of either a photopic or a scotopic luminosity function.[4]

The insertion of the special eyepiece (together with the removal of an aperture stop in the apparatus) has the effect of reducing the lumi-

[4] Because of the use of the Maxwellian view, the rays of light were not affected by the contraction of the natural pupil. Johnson (11) has discussed the resulting difficulty in specifying the photometric intensities of such stimulus fields. In the present experiment, the small (2°8′) field of white light reduced 3.7 log units by neutral density filters matches a comparison field of white light adjusted to 12.8 foot-lamberts and viewed with the natural pupil. Colored lights were provided by selective filters described by Riggs, Berry, and Wayner (23). On the basis of their calculations of the photopic equivalence of these stimuli we may state that each of the following combinations has the stimulating effect of a 12.8 ft.-L. field: White, with neutral density filters of 3.7 log units density; red (*C*) with 2.3 log units of neutral density filters; green (*G*) with 2.3 log units of neutral density filters; and blue-violet 76 with no neutral density filters. These stimuli are calculated to be roughly equivalent in their effectiveness for arousing the central cone receptor system of the retina.

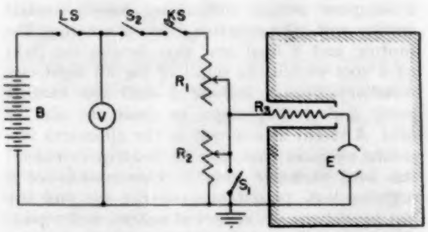


FIG. 4. Diagram of the circuit used for electrical stimullation of the eye. B, 90 volt battery; LS, line switch; V, voltmeter; S_1 S_2 cam operated switches; KS, experimenter's knife switch; R_1, R_2, resistance coils of potentiometer; R_3, fixed resistance of 200,000 ohms; E, stimulating electrodes.

Timing of the optical stimuli was provided by means of a rotating disc shutter that intercepted the beam at its narrowest focus. An open section of the disc permitted an exposure of 2 sec. during each cycle of approximately 15.3 sec. The "wiping time" for opening or closing the shutter was .03 sec.

Electrical system. A diagram of the apparatus for stimulating the eye with electric current is shown in Fig. 4. A D.C. voltage is supplied by the battery at B in the diagram. This is nominally a 90-volt supply but its actual value is indicated by the voltmeter, V. This voltage is divided by the use of a potentiometer circuit containing two Cenco decade resistor units, R_1 and R_2. The dials for these units were manipulated in such a way that the sum of the resistances set into R_1 and R_2 was always equal to 10,000 ohms. Thus, the voltage available for stimulating the eye was always proportional to the resistance set into R_2; specifically, this voltage, V_s, is given by the relation

$$V_s = \frac{VR_2}{10{,}000}$$

where V is the battery voltage indicated by the D.C. voltmeter. R_2 can be adjusted by fixed steps of 1 ohm from 0 to 10,000 ohms, but in actual operation steps of 10 ohms or more are used over a range of 1,000 to 7,000 ohms.

The electrodes at E consist of two silver plates held in contact with the skin of the brow and cheek at regions as near the eye as convenient directly above and below the eye. The cheek electrode has a square contact surface of 30 × 30 mm. It is grounded and serves as the cathode in electric stimulation. The electrode on the brow is a rectangle measuring 32 mm. long by 25 mm. high. The electrodes are held against the skin with approximately constant pressure by the use of a headband and spring device. Electrode paste is used to ensure good electrical contact with the skin. The electrical resistance is of the order of 4,000 ohms across these electrodes.

In series with the S is a fixed resistor, R_3, of 200,000 ohms. This is a precision resistor entirely enclosed within a metal shield. Two important functions are served by this arrangement. First, it limits the current that can flow through the S so that even a charge of several hundred volts in the experimenter's room would be harmless to the S. Second, it permits an accurate statement of the current flowing through the S in terms of the setting of R_2. The stimulating current, I_s, in amperes is given by the relation

$$I_s = \frac{V_s}{200{,}000 + R_s}$$

where V_s is the voltage supplied by the potentiometer as indicated above, and R_s is the resistance of the S. It will be noted that, with R_s typically about 4,000 ohms, even a relatively large change in R_s has very little effect on the value of I_s. It may therefore be said that, to an accuracy of one or two per cent, the stimulating current is proportional to the value of R_2 in the potentiometer, and its absolute value, I_s, may always be specified in terms of the above equation.

It has been found necessary to ground the stimulating circuit and place the S within an electrically shielded room. The cheek electrode was grounded, and the polarity of stimulation was such that the forehead electrode was made positive by reference to it.[8]

Timing arrangements. The switches S_1 and S_2 are microswitches actuated by a cam device mounted on the rotating disc shutter. The rela-

nance while increasing the size of the field in order to include more of the peripheral rod-receptive region of the retina. Now white light with 2.0 log units of neutral density is the equivalent of 11.3 ft.-L. Again referring to the work of Riggs, Berry, and Wayner we find that there is an approximate scotopic equivalence of white light with 2.6 log units of neutral density filters; red (*C*) with no neutral filters; green (G) with 1.5 log units; and blue 76 with no filters. These stimuli are calculated to be roughly equivalent in their effectiveness for arousing the peripheral rod receptor system of the retina.

[8] Motokawa has indicated that polarity has little effect on the degree of enhancement. We have confirmed this for the 0.1-sec. pulse duration used with the dark-adapted eye. Howarth's (10) experiments have shown that both on-and-off effects are found with this duration and that it is a suitable duration because the strength-duration curve has reached a steady value at about 0.1 sec.

tion between the open sector and the cam could be adjusted by reference to a radial scale, so that any desired delay time could be provided between the end of the light flash and the onset of the D.C. pulse. The cam operates in such a way that, just prior to the time at which a stimulus is to be given, S_1 is closed and then S_2 is closed. Then stimulation is begun when S_1 drops open, allowing current to flow through the *S*, and 0.1 sec. later S_2 drops open, thus terminating the flow of current from the potentiometer. These switches remain open until nearly the time for the next pulse, when they are closed in the order $S_1 \rightarrow S_2$ as before. While the full cycle of the shutter disc is 15.3 sec., it is possible to provide electrical pulses separated by only half of this interval by inserting a second cam in a position diametrically opposite to the first. This is ordinarily done for speeding up the determination of electrical thresholds in "dark" series, i.e., when no light flashes are involved. Control experiments have shown that similar thresholds are found with stimulus intervals of 15.3 and 7.65 sec.

The experimenter uses a noiseless knife switch, KS, to regulate the presence or absence of current, for those series in which the *S* must make a judgment of this kind.

Controls. The timing and intensity of electrical stimulation were continuously monitored by the use of a cathode ray oscilloscope. In addition, photographic records were made from time to time in which both the flash of light and the square-wave electrical pulse were registered on moving photographic paper. A Hathaway oscillograph was used for this purpose. This gave assurance that the various stimuli were being delivered at the proper times with the designated durations. It was found necessary to renew the microswitches from time to time. They typically delivered a clean square wave for several months of operation, but then developed a slight chatter or raggedness of action. Although the total energy of the stimulus was scarcely altered by this degree of irregularity, switches were discarded as soon as the raggedness became apparent on the oscillographic record.

Psychophysical Methods

Since one of the aims of the present series of experiments was to verify certain of the basic findings of Motokawa, it seemed important to use psychophysical procedures as similar as possible to those used in the original work. We have established a procedure for determining thresholds which incorporates the essential elements of the method which he originated and uses in his work.[6] Certain differences between this method, which will be called the limits-comparison (LC) method, and that of Motokawa will be discussed after the LC method is described.

The limits-comparison procedure. The LC method, as the name implies, is a two-stage procedure. It begins with a descending series of stimulus presentations, as in the conventional method of limits. The series is begun with the presentation of a stimulus which produces a clearly visible phosphene. The exact intensity of this first stimulus is varied from one determination to the next. After a positive response, the intensity of the stimulus is decreased to a value 98 per cent of the preceding one. This procedure is continued, with each electrical stimulus being 98 per cent of the preceding one, as long as the *S* continues to respond positively. When the *S* fails to see a phosphene, the same intensity is repeated on the next trial. If a phosphene is seen on the second presentation of the stimulus, the intensity is again lowered for the next trial. When the *S* responds negatively on two consecutive presentations of the same intensity, the second stage of the procedure is invoked.

The comparison stage of the method consists of presenting a pair of stimuli, one of which is a blank. The *S* reports which of the two is the test stimulus. The position of the blank, i.e., first or second, is randomized and established before the determination is begun. The *S* can respond by naming the position, first or second, at which he sees a phos-

[6] We wish to express our appreciation to Dr. Motokawa for sending us descriptions of his method and for visiting our laboratory with the purpose of acquainting us with the details of his procedure. The most detailed published accounts of Motokawa's procedure for determining thresholds are found in references 20, 21, and 22.

phene, or, if he cannot discriminate, by saying "I don't know." The *S* is instructed not to guess, and to make a judgment only if he is able to state which position is correct. After each judgment of position is made the experimenter tells the *S* whether he is right or wrong. For those trials in which the *S* is unable to state which position is correct, the experimenter does not inform him of the correct position.

The comparison procedure is started by presenting a pair of stimuli, one of which is a blank and the other a test stimulus whose intensity the *S* has failed to see on two consecutive presentations in the method of limits. If the *S* correctly identifies the position of the stimulus, the intensity is again decreased by 2 per cent and another comparison pair is presented. If the *S* makes an error in naming the position of the phosphene, a second comparison at the same stimulus intensity is presented. If this comparison is correctly judged, a third comparison at the same intensity is presented. If the third is also correctly judged, the intensity is decreased for the next comparison. Each time that the *S* reports that he cannot name the correct position, the same comparison pair is repeated. The criterion for threshold is three consecutive "I don't know" responses at a given intensity, *or* two incorrect responses out of three comparison pairs at a given intensity. These criteria are not combined; that is, one or the other must be met. An *S* can respond incorrectly once, say "I don't know" once or twice, and still continue to the next step by responding correctly on two further trials. The intensity of the criterion value is called threshold.

A record is kept of all stimuli presented during a threshold determination together with the *S*'s response to each. The number of minutes after the beginning of the session at which the determination is begun and ended are also indicated. Table 1 is a sample protocol for one threshold determination, showing the intensities presented (in resistance units) and the *S*'s responses.

TABLE 1

SAMPLE PROTOCOL ILLUSTRATING THE LIMITS-COMPARISON METHOD

(Subject WGL 4/29/54—Dark Threshold)

Limits Stage		Comparison Stage		
R_2 Setting	Response	R_2 Setting	Correct Position	Response
4090	Yes	3200	2	R
4010	Yes	3140	2	R
3930	Yes	3080	2	R
3850	Yes			
3770	Yes	3020	2	?
3690	Yes	3020	1	?
		3020	1	R
3620	No			
3620	Yes	2960	1	R
3550	Yes	2900	2	?
3480	Yes	2900	2	R
3410	Yes			
		2840	2	W
3340	No	2840	1	R
3340	Yes	2840	1	?
		2840	2	R
3270	Yes			
		2780	1	W
3200	No	2780	1	?
3200	No	2780	1	?
		2780	1	?

Threshold is at an R_2 setting of 2780 ohms, giving a current of 116 microamperes.

The interval separating the stimulus presentations is kept constant by means of the timing device described in the apparatus section. This interval is fixed at one of two values, depending upon whether the threshold is being determined with or without a flash of light preceding the electrical pulse. For reference or "dark" threshold determinations the intervals is 7.65 sec., while for "light" threshold determinations the interval is 15.3 sec. This doubling of the time interval is the only difference in the schedule for light and dark determinations. Control experiments have shown no difference in the precision or mean value of threshold determinations in the dark with each of the time intervals. The *S* is made aware that the stimulus is being presented by the sound of the switches being activated, as described earlier. No warning is given for the presentation of the light. The *S*, however, becomes familiar with the rhythm of the cycle and has no difficulty in being prepared for the light, or the phosphene. Once the thresh-

old determination is begun, no break or rest period is used. Stimuli are presented continuously until the threshold is reached. On the rare occasions when the *S* is unprepared for the stimulus because of a wink, cough, etc., he is allowed to ask for a repetition of that stimulus. He is not allowed to ask for a repetition of the stimulus for the sole purpose of re-evaluating it.

The time required to determine a threshold varies considerably from *S* to *S* and from one determination to another. The experimenter determines the starting point arbitrarily, attempting to estimate this value such that approximately eight to fifteen steps will be used in the limits method before the *S* begins the comparison stage. The initial presentation must be seen clearly by the *S*. If it is not, the determination is started again at a higher intensity. Ordinarily, at least four or five intensities are correctly judged in the comparison procedure before reaching threshold, but there is great variability in this. For a dark threshold, the total time taken varies from three to twelve minutes, with an average of about five minutes. When light is presented, this time is about twice as long.

Differences between the LC method and that of Motokawa. As stated earlier, an attempt was made to make the LC method as similar as possible to the method originated by Motokawa. The differences between these methods must be made explicit, however, so that the reader can consider these differences in evaluating the results.

Two differences between the methods appear to be of major importance. The first of these differences is in our use of equal log steps throughout all series of stimulus presentations. Motokawa's method is to use large steps of ten per cent or more in the beginning of a threshold determination (i.e., during the limits stage) and then to use small steps during the final portion of the comparison stage. Around threshold his steps are approximately one per cent differences. Motokawa does not establish the steps that he will use before the determination is begun.

Our own method has been to use a logarithmic series of predetermined stimulus intensities such that each successive step in the series is 2 per cent lower than the preceding one. Our reasons for insisting upon this mode of presentation are the following: (*a*) Results by the method of constant stimuli have shown that there is essentially a Gaussian probability relationship between the probability of seeing a phosphene and the log of the stimulating current. It is therefore appropriate to use equal log steps as the basis for any descending scale of stimulus intensities. (*b*) The use of equal log steps achieves, in a systematic way, Motokawa's twin aims of avoiding the use of very lengthy series of stimuli and yet basing a threshold determination on steps of small linear magnitude. (*c*) The use of equal log steps has the further advantage that there is no massing of stimuli at any one level of intensity. The probability of finding a threshold at any given intensity level is raised by increasing the number of stimuli presented at that level. In other words, an equal-step method is a safeguard against experimenter bias in the determination of thresholds. This point is discussed more fully in the final section of this paper.

The second major difference, related to the first, is in the rigidity of the presentation of stimuli and the criteria for threshold. Motokawa's observers are allowed to ask for the comparison procedure at any time during the limits stage at which they consider the detection of a phosphene to be difficult. They are also allowed to ask for a repetition of a comparison pair if they are not sure of a response, or if they are "confident" of a response which proves incorrect. Another feature of Motokawa's method is that he continues to present comparison pairs after the *S* is no longer discriminating. This is done because of the possible existence of multiple thresholds, considered important by Motokawa. The *S* of multiple thresholds will be treated later in this paper. The threshold criterion is not rigid in Motokawa's method, and a threshold is decided upon after this continuation of the comparison series has led to a number of failures to discriminate. Again in the interests of low variability and standardization of the procedure, in the LC method all stimulus presentations are determined by the *S*'s response to the previous stimulus, and the rigid criterion outlined above is used for establishing the threshold.

Subjects

The reliable observation of an electrically aroused phosphene is a task which requires rather extensive training. As a consequence, all of the experiments to be reported have used a small number of trained *S*s, usually three or four *S*s per experiment. Most of the *S*s took part in several of the experiments.

The *S*s were laboratory personnel, including graduate students and two of the authors. All were tested by Ishihara

plates (5th ed.) and found to have normal color vision. Those *Ss* who customarily wore glasses were allowed to wear them during the experiments. Most of the *Ss* were familiar with the general purpose of the experiments, but every effort was made to prevent them from responding in terms of extraneous cues, forced choices, or preconceived notions. In judging single stimuli they were instructed to pay no attention to serial position but to call each as it appeared to them. In the case of paired stimulations they were asked to designate the one that appeared to be the stronger of the two, but were never forced to choose between two that appeared equal.

All *Ss* were trained for from eight to ten one-hour sessions prior to taking part in an experiment. This training consisted of practice in observing and reporting phosphenes, in distinguishing phosphenes from blank stimuli, in following the routine of the limits-comparison procedure, and in observing phosphenes after light flashes. Training was continued until all *Ss* arrived at a point where repeated thresholds under the "no-light" condition were reasonably stable. As training progressed the discrepancy between thresholds determined under similar conditions decreased markedly. By the end of the training period the second of two consecutively determined thresholds seldom differed by more than 15 per cent from the first. Only one *S* was not able to achieve this degree of stability and found it difficult to distinguish a test stimulus from a blank. He was not used in the experiments.

Evaluation of the Limits-Comparison Procedure

Experiment I. The Reliability of Threshold Determinations

The LC procedure has been used in the majority of our experiments for the following reasons: (*a*) It is basically the method developed and used by Motokawa in obtaining the specific wavelength effects in which we are primarily interested. (*b*) The procedure is relatively fast. A simple threshold may typically be determined by a single LC run of about five minutes' duration. A comparable determination by the constant stimulus method would take 15 to 20 minutes, and a similar time would be required for a typical set of ascending and descending series in the method of limits. The slower methods cannot well be used in sessions involving the ten or more threshold determinations that we have found necessary to use in the present experiments.

Since the LC procedure is a relatively new one, there is little information as yet on its reliability except for the reports of Motokawa and his associates. The numerous papers by Motokawa convey the impression of extraordinary reliability in the obtained electrical thresholds. Specifically, there is the statement that successive determinations of a reference threshold ordinarily agree within a few percentage points; a discrepancy as large as 10 per cent is relatively uncommon for these reference thresholds taken at various times during a given experimental session. A discrepancy as large as this is taken by Motokawa to mean that something is wrong with the results of that session, and they are discarded.

The high reliabilities reported by Motokawa for his limits-comparison data are certainly not typical of absolute threshold determinations in general. Agreement within 0.1 log unit (or about 20 per cent) is ordinarily considered quite satisfactory for individual determinations of absolute thresholds in such an experiment as the course of dark adaptation. Howarth (10), Clausen (5), and Gebhard (6) have stated that they were unable to achieve such a high degree of reliability. It therefore seemed desirable to make a detailed comparison of the reliabilities of the new LC method and the conventional method of

constant stimuli (CS). The design of the experiment is such that each experimental session provides data from both methods on the same *S*s under the same experimental conditions. It must be realized, however, that the LC method as used here is not precisely the method originated by Motokawa. It has been modified as described above in the interests of greater objectivity.

Specifically, we have performed a balanced-order experiment in which half of the time was spent in determining absolute electrical thresholds by the LC method and half of the time by the conventional CS method. A sufficient number of replications were obtained so that conclusions could be drawn with regard to the variability of threshold determinations by each of the two methods and the absolute magnitudes of the thresholds obtained by each. Due account was taken of the fact that the CS method requires a much longer time for threshold determinations. No attempt was made to find thresholds following flashes of light in this portion of the experiments, because it was felt that reference thresholds in the dark were basic to all the findings reported by Motokawa and that the method could more conveniently be evaluated by the use of simple conditions.

Psychophysical procedure. Experiment I compares the LC method, as described above, with the conventional method of constant stimuli. The CS method was used as follows to determine the threshold for electrically induced "phosphenes." Seven stimulus values, separated by equal log steps, were used. Each intensity was judged 20 times. A random arrangement of the seven intensities was presented at the rate of one stimulation every 7.65 sec. After a total of 70 presentations, 10 at each intensity, a one-minute rest period was given. The order was then repeated in the opposite direction, making a total of 140 presentations. Six blank stimuli were inserted into the order at random intervals and the *S* was informed of the blank after his judgment was given. This served to warn the *S* against false positive judgments.

The *S*'s task was to make a judgment on the presence or absence of a phosphene at each stimulation. He called "yes" or "no" after each and his response was recorded. No comments were made by the experimenter except following the response to a blank stimulus, when the *S* was told that the stimulus had been blank. If the *S* missed a presentation by being unprepared for it, he was allowed to omit it and the stimulus was repeated at the end of the series.

The percentage of "yes" judgments at each stimulus intensity was calculated and plotted on a probability plot against the log of the stimulating current. A straight line was fitted by eye to the points, and the threshold was taken as the intersection of this line and the 50 per cent level on the probability scale. No threshold was considered as part of the data unless the percentage of "yes" judgments covered at least the range from 25 per cent to 75 per cent for the intensities used.

Plan of each Session. Each session of Experiment I consisted of two constant stimulus (CS) threshold determinations, each taking 20 minutes to obtain, and two 20-minute blocks of threshold determinations by the limits-comparison (LC) method. The LC blocks could not be exactly 20 minutes in duration, since the time required to obtain a threshold varies. In this case, several thresholds were obtained within a period of approximately 20 minutes. The number of thresholds determined in 20 minutes

varied from two to five. A one-minute rest followed the first and third 20-minute periods in the session; and a three-minute rest followed the second period. Preceding the first period there was a 15-minute period of dark adaptation. During the latter part of this dark-adaptation period one threshold was determined by the LC method. This threshold was not used as part of the data, but served as a "warm-up" for the *S*. It also gave the experimenter an indication of the level of sensitivity for that day, allowing him to select appropriate starting points for the later LC determinations.

Experimental design. Experiment I consisted of 16 of the sessions just described. These were held approximately three times a week and no two were ever held on a single day. The two methods of threshold determinations, LC and CS, were presented in an ABBA order on half the sessions and a BAAB order on the other half. The presentation of the two orders was balanced.

The same seven intensity values were used for a given *S* for each of the 32 thresholds determined by the CS method. The values were selected on the basis of preliminary work with each *S*, and were not changed after the experiment was under way. As a result, there were a few instances in which no threshold could be determined for a given period because of failure to satisfy the condition that the positive judgments cover at least the range from 25 per cent to 75 per cent over the series of intensities used.

Three *S*s participated in this experiment. All had had previous training in observing phosphenes and in the routine of the LC method, as described in an earlier section. In addition, all had had practice with the CS method, during which the range of intensities to be used in Experiment I was established. This range was .40 log unit (96 to 242 μa) for LAR, .476 log unit (63 to 188 μa) for SHH, and .476 log unit (84 to 251 μa) for WGL.

Results. The data from Experiment I allow two types of evaluation of the LC method of determining phosphene thresholds. First, this method can be compared with a more conventional psychophysical procedure, the CS method. Second, the large number of threshold determinations by the LC method makes possible an internal analysis of the characteristics of this new psychophysical procedure.

A comparison of the limits-comparison and constant stimulus methods. It has been noted that the LC method requires less time for the determination of a single threshold than does the CS method. For the purpose of comparing the methods and balancing times, an equal amount of time during each session was spent on each method. Thus, there were four 20-minute periods in a single session, two spent on each of the two methods. Since a single period for the LC method allows time enough for the determination of from two to five thresholds, while only one was obtained in each period with the CS method, the means of the several LC thresholds in a given period are compared with the CS threshold value. However, an outstanding advantage of the LC method is its quickness, and the method is typically employed for single determinations of threshold. It is therefore necessary to compare single LC thresholds with CS thresholds. In the results tabulated below the comparisons of the LC and CS methods are made both for the mean LC threshold for a period and the first LC of a period.

TABLE 2

THRESHOLD VALUES OBTAINED BY THE LIMITS-COMPARISON PROCEDURE (LC) AND BY THE METHOD OF CONSTANT STIMULI (CS) DURING EXPERIMENT I

(Values in the body of the table are resistance settings of R_2 in ohms)

Subject LAR

Day	LC		CS	CS	LC		Day	CS	LC		LC		CS
	1st	Mn			1st	Mn			1st	Mn	1st	Mn	
1	2840	3220	3700	3990	3930	3950	2	3440	3410	3410	3200	3500	4240
4	2840	2880	3490	3490	2960	2900	3	3600	2780	2870	2530	2820	3870
6	3200	3050	3700	3870	3200	3260	5	3250	2680	2750	2730	2700	3700
7	3080	2930	3730	3730	3340	2990	8	3840	3340	2990	3080	2930	3650
10	3480	3070	3320	—	2780	2700	9	3760	3020	2790	2730	2730	3390
11	3080	2750	3590	3630	3200	3170	12	3930	3200	3170	2780	2790	3440
13	2230	2600	3270	3410	2900	3030	14	3490	3550	3680	2900	3090	3620
16	2580	2380	3140	3390	2780	2730	15	3570	3340	3150	2960	3020	3670
Mean	2916	2860	3492	3644	3136	3091		3610	3165	3101	2864	2947	3697

Subject SHH

Day	LC		CS	CS	LC		Day	CS	LC		LC		CS
	1st	Mn			1st	Mn			1st	Mn	1st	Mn	
2	2330	2230	2450	2940	2630	2530	1	2740	2780	2740	3020	2960	3020
3	2330	2400	2540	2540	2480	2560	4	2360	2330	2240	2430	2190	2660
5	2280	2100	2360	2420	2840	2950	6	2600	2630	2650	2680	2660	2600
8	2030	2280	2390	2540	2730	2600	7	2580	2630	2930	3080	3100	—
9	2330	2430	2520	2580	2110	2220	10	2390	2530	2360	2480	2430	2470
12	2580	2480	2430	2490	2330	2670	11	2500	2430	2380	2530	2460	2410
14	2030	2260	—	2400	2580	2480	13	2350	3270	3200	2780	2780	2670
15	2280	2530	2470	2570	2780	2760	16	2580	2680	2880	3270	2920	2370
Mean	2274	2339	2451	2560	2560	2596		2512	2660	2672	2784	2687	2600

Subject WGL

Day	LC		CS	CS	LC		Day	CS	LC		LC		CS
	1st	Mn			1st	Mn			1st	Mn	1st	Mn	
2	3340	3240	3100	3500	3140	3380	1	3130	3770	3270	2580	2430	2960
3	2680	2960	2880	2660	2780	2860	4	2690	3080	2760	3410	3130	2750
5	2630	2560	—	—	3770	2880	6	2980	3080	2940	2580	2510	2900
8	3020	2900	2960	3340	2630	2460	7	3120	2840	3200	2580	2790	3240
9	3550	3370	3040	3040	2900	2990	10	3340	3410	3840	3480	3430	3370
12	3410	3410	2870	3370	2900	2780	11	3310	3270	3340	3690	3450	3570
14	2780	2840	3070	2840	2840	2680	13	3140	2530	2320	2110	2090	3070
15	3270	2960	3010	2830	2730	2900	16	3100	3200	2770	2840	2820	2930
Mean	3085	3030	2990	3083	2961	2866		3106	3147	3055	2909	2831	3099

Absolute thresholds obtained by the two methods. Table 2 presents the CS threshold, the mean of the LC thresholds, and the first LC threshold for each of the four periods of each of the 16 sessions for each of the three *Ss.*[7] Figure 5 shows the means of these values. It will be noted that each value shown in Fig. 5 is the mean of eight

[7] The missing values for CS thresholds result from a failure to meet the criterion of basing a threshold on percentages of positive judgments running from 25 per cent or less to 75 per cent or more.

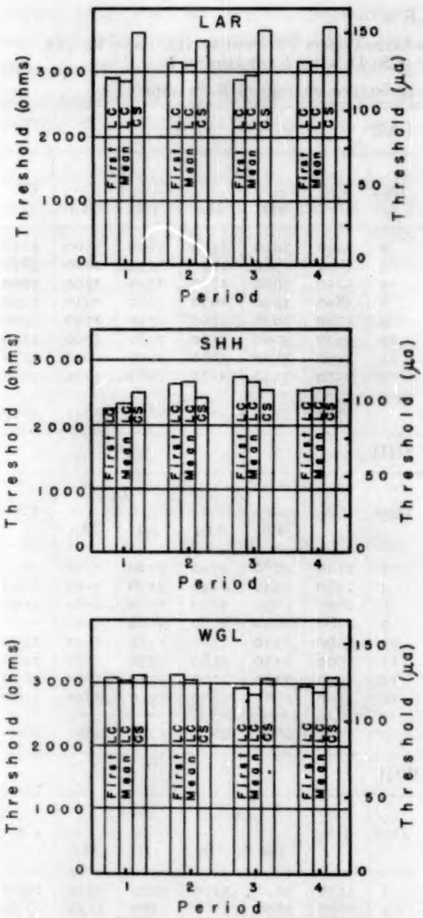


FIG. 5. Mean thresholds for the elicitation of phosphenes in the dark-adapted eye. Threshold values for the first LC, mean LC, and CS determinations in the four periods of Experiment I. The individual thresholds and their means are tabulated in Table 2.

sessions. The CS method was used eight times in each period in the 16 sessions, and the same is true for the LC method. Thus, in the bar diagrams of Fig. 5, Periods 1 and 4 for a given method represent the same eight sessions of the experiment, while Periods 2 and 3 represent the other eight sessions.

TABLE 3

OVER-ALL MEAN THRESHOLD VALUES

(Values of R_2 in ohms for all periods combined for each method)

Subject	CS	LC(mean)	LC(first)
SHH	2531	2574	2569
WGL	3070	2946	3026
LAR	3610	3000	3020

It can be seen from Fig. 5 that there is no consistent tendency for the threshold to increase as the session progresses for either method. It must be remembered that the *S*s were dark-adapted for 15 minutes prior to the first period of a session. Hence the rapid changes in threshold that are found during dark adaptation (Achelis and Merkulow, 1; Lewis, 12) are not of any consequence here.

A second finding evident from Fig. 5 is the similarity of absolute threshold values for the two methods as evidenced by two of the *S*s, SHH and WGL. The other *S*, LAR, had a consistently higher threshold when measured by the CS method. The over-all means for the three measures are presented in Table 3.

Variability of thresholds obtained by the two methods. Experiment I was designed so that the two methods (LC and CS) could be compared with regard to their within-session variability. Thus, each session consisted of two periods on each of the methods. Further, for half of the sessions a given method was used to determine thresholds in adjacent time periods (Periods 2 and 3) and for the other half the same method was used in separated time periods (1 and 4). Hence, the within-session variability of the methods can be compared for each set of time conditions. The day-to-day variability of electrical threshold determinations is large, and experiments on

this phenomenon are best designed so that thresholds taken on different days are not directly compared. Therefore, this type of variability will not be considered here.

The basic measure that will be considered here is the average within-session change for each method. The measure is obtained by computing the difference between the two thresholds determined by the CS method, for example, in a given session. Since the methods were presented in an ABBA order on half the sessions and a BAAB order for the other half, there will be, for each *S*, eight differences between Periods 2 and 3 for the CS method and eight differences between Periods 4 and 1. The mean of these eight differences gives a measure of the average change, or within-session variability for that method. An example of the computation of this average change is given in Table 4.

The differences in Table 4 were obtained by subtracting the threshold obtained in Period 1 from the threshold obtained in Period 4 for each of the sessions in which the CS method appeared in these periods. Reference to Table 2 in which these thresholds are presented may clarify the procedure. The mean of these values is obtained, both with and without regard to the sign of the difference. A positive difference indicates that the threshold was higher, i.e., less sensitive in the later period. The algebraic mean is used as the basis for the calculation of the variance of the measure.

TABLE 4
SAMPLE COMPUTATION OF THE AVERAGE CHANGE IN THRESHOLD VALUES
(Subject WGL-CS Method; Period 4 − Period 1)

Day	Difference
1	−170
4	+ 60
6	− 80
7	+120
10	+ 30
11	+260
13	− 70
16	−170
Mean (algebraic)	− 2.5
Variance	22221.
Mean (absolute)	120

The above tabulation was followed for both the CS and the LC methods. For the LC method, it was done twice, once for the mean LC of the period and once for the first LC of the period. It was done for both the adjacent periods (3-2) and separated periods (4-1). Two main comparisons emerge from this tabulation. First, the absolute size of these within-session differences is of interest. The size typical of these differences is an indication of the variability of thresholds determined by each method. Second, the algebraic mean of these differences is also important, since it provides for the assessment of trends through the session. Positive mean differences would indicate a decrease in sensitivity as the session progresses. The algebraic mean is also the proper basis for a variance measure. Knowing the variance, one can make a statement of the limits of confidence of a given difference. Tables 5 and 6 present the results of this analysis of the two methods. In Table 5 the algebraic and absolute mean changes are presented, together with the over-all mean threshold values for each *S*. The mean thresholds, combining all periods, are presented in order to give meaning to the magnitude of the differences presented. Table 6 presents *F* ratios, comparing the variances of the methods.

A consideration of Table 5 shows that the CS method has generally given more reliable thresholds than has the LC

TABLE 5

AVERAGE CHANGES (OHMS, ALGEBRAIC AND ABSOLUTE) OF THRESHOLDS OBTAINED IN A SINGLE SESSION OF EXPERIMENT I BY A SINGLE METHOD

	LAR		SHH		WGL	
	Absol.	Algeb.	Absol.	Algeb.	Absol.	Algeb.
CS Method						
Period 3-2	127.14	+127.14	131.43	+131.43	272.86	+92.86
Period 4-1	350.00	+87.50	182.86	+97.14	120.00	−2.50
Mean Threshold	3610		2531		3070	
LC Method (mean)						
Period 3-2	176.25	−153.57	132.50	+15.00	356.25	−223.75
Period 4-1	323.75	+231.25	310.00	+257.50	278.75	−163.75
Mean Threshold	3000		2574		2946	
LC Method (1st)						
Period 3-2	313.75	−301.25	258.75	+123.75	443.75	−238.75
Period 4-1	395.00	+220.00	403.75	+286.25	448.75	−123.75
Mean Threshold	3020		2569		3026	

method. This conclusion is based on the average discrepancy between thresholds determined in the two periods of each session devoted to a given method. The average discrepancy for the CS method is lower than that obtained with the LC method even when due allowance is made for the fact that individual LC runs take less time than the CS determinations. The magnitude of the discrepancy relative to the size of threshold is in every case less than 10 per cent for the CS method, less than 15 per cent for the LC mean, and less than 20 per cent for the first LC. The average discrepancy between the adjacent periods, three and two, is consistently smaller than that of Periods 4-1 for LAR and SHH, but not so for WGL. These 3-2 period changes are of particular interest, since they indicate the variability of thresholds determined closely in time, as in the typical experimental situation. Since they are generally smaller than those determined far apart in time, it is concluded that reference determinations should be repeated frequently.

The algebraic differences, also shown in Table 5, are not consistently positive; in other words, the threshold does not appear to exhibit a rising trend during the session. One of the *S*s, SHH, does show some tendency toward a rise in threshold. Another *S*, WGL, shows the

TABLE 6

F RATIOS OF VARIANCE OF AVERAGE CHANGES

	LAR		SHH		WGL	
	LC_{mn}/CS	LC_{1st}/CS	LC_{mn}/CS	LC_{1st}/CS	LC_{mn}/CS	LC_{1st}/CS
Period 3-2	3.494	2.853	1.411	3.961	1.407	2.559
Period 4-1	1.672†	1.353	1.925	3.007	4.382*	15.153**

* $p<.05$.
** $p<.01$.
† In this case the CS variance was greater than the LC variance.

opposite trend as indicated by negative values in all but one of his discrepancies.

The *F* ratios shown in Table 6 point out the fact that in all but one case the variance of the LC method changes was greater than that of the CS. Only for LAR, 4-1 period difference, was the CS more variable than the LC mean but not more variable than the LC first. None of these ratios for the 3-2 period difference is significant. For the Period 4-1 difference, they are significant for WGL, again indicating that frequent determinations of a reference threshold are desirable. Variances combining the 4-1 and the 3-2 periods were also computed for both methods. Here the LC difference variance was always greater than the CS. None of these was significantly greater when the mean LC was used, but for two *Ss*, WGL and SHH, the LC first/CS ratio was significant. When the variance of the first LC is compared to that of the mean LC, no significant differences are found for any *S*. In all but one case, however, the first LC variance was greater than the mean LC.

Characteristics of the Limits-Comparison Procedure

Variability. The large number of repetitions of the limits-comparison method (two to five in each 20-minute period) makes it possible to compute the variability of thresholds determined by this method. Since the method involves presenting equal log steps, each representing approximately a 2 per cent decrement in stimulus intensity, the difference between any two thresholds may be expressed as the number of these steps separating the thresholds. It is convenient to make use of these step units for the purpose of setting up a distribution of differences between adjacent thresholds.

The details of the procedure which has been used to get at the question of variability are as follows. In each period there are several thresholds obtained by the LC method. The differences between successive thresholds within each period are found. These differences between the first and second, second and third, etc., are tallied for each *S*. The result is a distribution of differences, the mean of which represents the mean discrepancy between one threshold value and the next. The standard deviation of this distribution can be used to estimate fiducial limits of this discrepancy. As in the earlier computation of differences, this mean difference has been computed algebraically, to assess trends and to compute the variance, and absolutely, to estimate the average size of the discrepancy independent of direction.

The results of this analysis are seen in Table 7. The discrepancies in this table are expressed in step units.

A positive value in the algebraic mean data of Table 7 indicates that the second threshold was higher, i.e., less sensitive, than the first. The values labeled transition threshold will be considered in the next section. It may be noted that for

TABLE 7
AVERAGE ADJACENT THRESHOLD CHANGE
(in 2 per cent step units)
LC Method

	Absolute Mean	Algebraic Mean	*N*	*SD*
LAR				
LC Threshold	4.77	−.46	71	5.84
Transition Threshold	3.61	−.06	71	4.49
SHH				
LC Threshold	3.41	−.03	59	5.11
Transition Threshold	3.95	+.15	59	4.96
WGL				
LC Threshold	5.10	−1.01	69	6.53
Transition Threshold	5.19	−1.30	69	8.15

each *S* the LC threshold difference is negative, but not large. From the information in Table 7, it can be predicted that the second of two adjacent thresholds will fall, 68 per cent of the time, between the limits of 6.30 steps below the first to 5.38 steps above the first for LAR, 5.14 steps below to 5.08 steps above for SHH, and 7.54 steps below to 5.52 steps above for WGL. The above values are obtained by taking one standard deviation above and below the mean discrepancy. Since each step represents approximately a 2 per cent change, the percentage discrepancy expected can be computed approximately by multiplying the above values by two.

Limits method vs. LC method. Since the first stage of the LC method is the descending phase of the conventional method of limits, a question arises as to whether the reliability of the method is increased by adding the comparison stage of the method. Motokawa reports that the method of limits by itself, without a comparison phase, is not sufficiently sensitive to be applicable to the study of electrical thresholds.

Although the present experiment did not include a direct comparison of the LC method with the method of limits, it is possible to make a comparison between threshold values obtained with the LC method and the transition intensity, i.e., the value at which the limits stage of the method was terminated by the occurrence of two successive judgments of "No." It should be pointed out that this value, which may be called the "transition threshold," is not actually equivalent to a threshold obtained by the usual method of limits, since the *S* was aware that the second, or comparison, stage was to follow. However, an analysis of these transition thresholds can serve as an estimate of the variability which would be expected from the method of limits. Clausen (5) has compared the comparison method with the method of limits, using both ascending and descending series for the latter. While it is not clear that he made any allowance for the differences in time taken by the two methods, he concludes that the limits method yields threshold values higher but less variable than those obtained by the comparison procedure. It is clear that the transition threshold must always be higher than the LC threshold. However, the variability of the transition threshold can be compared with that of the LC threshold. The procedure followed to obtain the adjacent threshold discrepancies for the transition thresholds is exactly as described for the LC method thresholds. Table 7 includes these values. It will be noted that the changes obtained when the transition threshold is used are very similar to those obtained by the LC method, and that no consistent trend occurs in any of the three *Ss*.

We may conclude that the comparison phase of the LC method has failed to contribute to the reliability of thresholds obtained by the limits phase alone. The LC method was nevertheless used throughout the major portion of our experiments for the following reasons: (*a*) It is the basic method used by Motokawa to study specific wave-length effects, (*b*) it yields thresholds that are lower, and hence presumably more sensitive to the aftereffects of light, than those obtained with the limits procedure alone, and (*c*) the method has the advantage of maintaining the *S*'s interest by informing him of the correctness or incorrectness of his comparison judgments.

Characteristics of the constant stimulus method. The data obtained by the CS method were typical of absolute

threshold data in general. The results of each threshold determination were plotted on probability paper, with percentage of "yes" responses on the probability ordinate and log stimulating current in microamperes on the abscissa. The resulting points showed the usual degree of conformity to a linear relationship. A straight line was fitted by eye to the points of each graph. There were 32 graphs for each *S*, two on each of the 16 sessions.

One index of the precision of the judgments is given by the ratio between the intensity that gives 75 per cent judgments of "yes" and the intensity that gives 25 per cent judgments of "yes." The mean value of this ratio is 1.42 (.152 log unit) for *S* LAR, 1.75 (.244 log unit) for *S* WGL, and 1.53 (.185 log unit) for *S* SHH. The standard deviations of the distributions of these values, expressed in log units, are 0.027, 0.053, and 0.049 respectively.

During the course of each threshold determination six blank stimuli were presented. That means that a total of 192 blanks were presented during the 32 determinations for each *S*. The numbers of false positive responses obtained with these stimuli are as follows: For *S* LAR, one (0.5 per cent); for WGL, 28 (14 per cent); and for SHH, 20 (10 per cent).

Conclusions with Regard to the Limits-Comparison Procedure

A conservative conclusion from the results of Experiment I is that the limits-comparison method has not proven to be more reliable than the conventional method of constant stimuli in the determination of thresholds for the appearance of phosphenes in response to electrical stimulation. Furthermore, the over-all precision that we have found for the electrical thresholds is not so high in any of these experiments as in the ones reported by Motokawa. In the final "Discussion" section of this paper we have attributed the phenomenally low variability in Motokawa's data to the use of psychophysical procedures that serve to curtail the range of intensities within which a given threshold is likely to be found.

Application of the Limits-Comparison Procedure to the Study of Enhancement

General Procedure

Electrical stimulation experiments are of interest chiefly in the possible interactions between electrical and photic stimuli. Motokawa has reported that the aftereffect of a flash of light is nearly always to enhance the sensitivity of the eye to electrical stimulation. The remainder of the present experiments consists mainly of determining the amount and time course of this enhancement following single flashes of light. The procedure is first to find the basic sensitivity of the eye by determining the absolute threshold for electrical stimulation in the dark. Then successive flashes of light are presented, and the corresponding threshold is determined for electrical stimuli presented at a given delay time after each flash. The degree of enhancement is then expressed as the ratio of electrical sensitivities determined with and without the flash of light. This has been done for a number of different experimental conditions with regard to delay time, intensity of light, area of light, wave length of light, and certain procedural variations. The basic procedure is described below. In all the experiments dealing with the effects of light upon sensitivity to electrical stimulation, the LC method has been employed.

A single experimental session. The

experimental session is begun with the positioning of the *S*'s biting board so that the light enters the pupil of the right eye. This is accomplished by turning on the light and allowing the *S* to make adjustments in the position of the biting board. The *S* learns to do this by looking successively up, down, to the right, and to the left, meanwhile adjusting the biting board so that the light disappears at about the same degree of rotation for each quadrant. After this is accomplished, the light is turned off and the *S* is dark-adapted for 20 minutes. During the latter part of this dark-adaptation period one threshold is determined by the LC method, under the no-light condition. This threshold is not used as a part of the data but serves merely as a practice determination.

After the *S* has been in the dark for approximately 20 minutes, the first dark, or reference, threshold is determined.[8] Following this, a "light threshold," i.e., an electrical stimulation threshold with light preceding each electrical stimulation, is determined. Next, another dark threshold is determined. This alternation of dark and light thresholds is continued throughout the session. The first threshold and the final threshold of every session are dark thresholds. Hence each light threshold may always be compared with the mean of two dark thresholds, i.e., those immediately preceding and following it. A one-minute rest period separates the succeeding threshold determinations, and no rest periods are allowed during any single determination. As previously described, intervals of 7.65 sec. separate stimuli in the dark condition and 15.3 sec. in the light.

[8] Previous experiments (Achelis and Merkulow, 1; Lewis, 12) have shown that the electrical threshold does not follow a course similar to the light threshold during dark adaptation. It is fairly stabilized at 20 minutes.

The time required for a single session varies considerably, depending upon the number of light thresholds determined and the time required for each threshold. In general, the sessions were designed to last one to two hours, including the period of dark adaptation. Occasionally longer sessions were undertaken, in order to get a large number of points in one session. No single session exceeded two and one-half hours in duration.

Computation of the effects of light. The effect of a light flash on electrical sensitivity will be designated in the present experiments in terms of an enhancement value ε. Enhancement is defined as follows:

$$\varepsilon = \log \frac{I_d}{I_l}$$

or, more simply,

$$\varepsilon = \log I_d - \log I_l$$

where I_d is the mean of the two "dark" thresholds (i.e., the electrical thresholds determined immediately preceding and following the determination of the "light" threshold) and I_l is the "light" threshold itself. All values of I are in terms of electric current in microamperes. It should be stressed that ε is calculated with reference to the dark values that surround the particular light threshold for which the value of ε is obtained. In this way, the effects of changes in electrical threshold which might occur during the session as a result of fatigue, etc., are minimized in the calculation of ε.

Differences from Motokawa's procedure. An important modification of Motokawa's procedure which has been introduced here is the practice of repeating dark, or reference, thresholds before and after each light determination, and the use of the mean of these two as a basis for calculating the effects of the light. Motokawa begins

each session with a dark determination, and occasionally repeats this throughout the session, but apparently does not do so systematically. He uses the original value for calculating effects of light, and the repetitions serve only as a check on the stability of the *S*. If a later dark threshold differs from the original by more than 10 per cent, Motokawa discards the data for that session. In the present experiments, however, no data are discarded, and a mean of the two dark thresholds is taken regardless of the magnitude of the discrepancy between them.

Instead of Motokawa's ζ, as an expression of the enhancing effect of light, ε values are used in the present experiments. ε has the advantage of being expressed in logarithmic units as deemed appropriate in these experiments. It carries with it the property that equal percentages of enhancement or depression of electrical excitability are represented by equal positive or negative values of ε. In other words a depression of the threshold of six step units or an enhancement of six step units has the same absolute value on a log scale when expressed as ε, but different values when expressed as ζ. This modification of Motokawa's procedure is not in the same category as those discussed earlier, however, since it involves no change in experimental procedure, but merely a slightly different way of expressing the data. It may be noted that ζ and ε each have a value of zero when no enhancement is present, and that ζ and ε have similar positive and negative values for all small amounts of enhancement or depression.

Experiment II. Enhancement Following Flashes of Light From a Small Central Field

A conclusion of major importance in Motokawa's work is that the course of enhancement following a flash of light reaches a peak at a certain delay time. The delay time for this peak is called the crest time, and its value is said to depend chiefly on the *color* of the preceding flash of light. Experiment II was designed to test the dependence of crest time on color in as direct a fashion as possible.

Procedure. Since there was not enough time in any one experimental session to vary both color and delay time, a single color was used on any given day. Enhancement values were determined for this color at the three delay times (1, 2, and 3 sec.) designated by Motokawa as the crest times for red, green, and blue lights respectively. The results were then evaluated simply by observing the degree to which the use of a red light, for example, resulted in a greater enhancement value at one second than at two or three seconds when these three enhancement values were found within a given experiment session. The design of the experiment was balanced in such a way as to minimize the factor of order of presentation within each session and from one session to another.

Stimulating conditions. The lights whose effects upon electrical sensitivity were measured in this experiment were presented by means of the optical system previously described. The 2°8′ field was used, and the duration of the light was two seconds. The intensities of the red, green, blue, and white light were equated at approximately 13 ft.-L. by the use of neutral density filters. The specific red, green, and blue colors were achieved by the use of the selective filters described in the apparatus section of this paper. The delay between the end of the two-second light flash and the electrical stimulation was set at 1, 2, or 3 sec.

Experimental session. During a single session in this experiment, the threshold following stimulation with one color was determined for each of the three delay times. The procedure used for a single session is described in the preceding section. The LC method was used to determine all thresholds. The initial electrical stimulation in each threshold determination was kept at the same general level for the light and dark determinations. Each descending series of electrical stimuli following flashes of light was started at the same intensity as the preceding dark. The starting intensities for

the dark determinations were decreased or increased by one step in a systematic fashion through the four determinations of a session. The *S*s were unaware of this manipulation of the intensity with which the descending series began.

Experimental design. Four *S*s participated in Experiment II, which consisted of eight sessions. Each of the three colors and white light were used in two sessions. The delay times were presented in the order 1, 2, 3 sec. for one of these sessions, and 3, 2, 1 sec. for the other session, for a given color. The colors were presented in an ABCDDCBA order through the eight sessions. Each of the four *S*s began the series with a different color. The first delay time used in the session, 1 or 3 seconds, was alternated for the eight sessions. That is, in Session 1 the first delay time was 1 sec.; in Session 2, it was 3 sec.; in Session 3, 1 sec., etc. Two of the *S*s started with a 1-sec. delay in Session 1 and two began with a 3-sec. delay.

Results

Effects of delay time on enhancement. The results of Experiment II are expressed as enhancement values (ε) computed from each of the thresholds following stimulation by light. The data of each session are presented separately. Figure 6 presents the two replications for each color for each of the four *S*s. The abscissa of each of the 16 graphs presented in Fig. 6 is the delay time, i.e., the time in seconds between the end of the 2-sec. flash of light and the onset of the 0.1-sec. pulse of electrical stimulation. The ordinate of each is ε, the enhancement of the electrical sensitivity by light as defined above. The points designated by *x*s represent the enhancement values obtained during the first session with a given color and the *o*s the second session. Each enhancement value is based on a single threshold in the "light" condition as compared with two "dark" thresholds, i.e., those immediately preceding and following the "light" series.

It should be pointed out again that Motokawa reports that the maximum enhancement effect for blue light reliably occurs at 3 sec., for green and white light at 2 sec., and for red light at 1 sec. *The data in Fig. 6 show no such consistent "crest times."* It is also evident that the light does not consistently have the effect of enhancing the sensitivity to electrical stimulation. Instead, many of the points in Fig. 6 show "negative enhancement," and many are approximately zero. The *S* LAR is the only one who shows consistently "positive enhancement."

In general, for all four *S*s, the enhancement resulting from stimulation by blue light is greater than that from the other two colors or white light, whereas red, green, and white have approximately equal effects within the individual subjects.

Variability. It is evident from Fig. 6 that there is a good deal of session-to-session variability in the enhancement values for a given color and delay time. For each color and delay time, the two enhancement values obtained on separate days were indicated by *x*s and *o*s. Table 8 gives the mean discrepancy for all corresponding values of ε. Each of these means is for differences, both absolute and algebraic, together with the standard deviation of the algebraic values. Also given is the mean of the discrepancies between "dark" thresholds obtained before and after each light threshold. It can be seen from Table 8 that there is no consistent tendency for the enhancement value obtained on the second day to be higher (i.e., with a positive mean difference) or lower (with a negative mean dif-

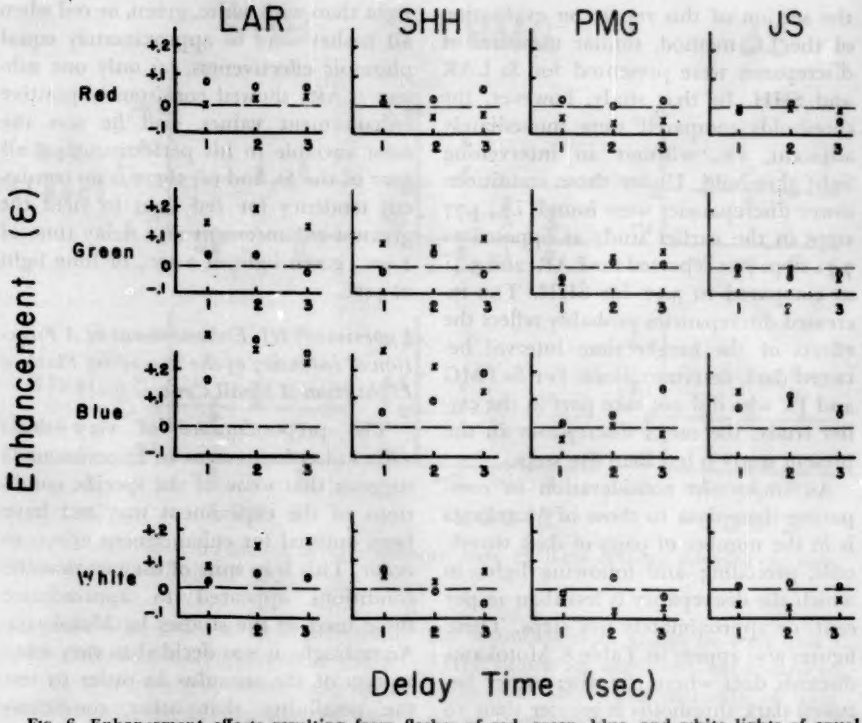


FIG. 6. Enhancement effects resulting from flashes of red, green, blue, and white lights of equal photometric luminance in Experiment II. The points designated by *x*s are for the first session and the *o*s for the second session. The "delay times" of 1, 2, and 3 sec. are measured from the end of the 2 sec. flash of light to the beginning of the 0.1 sec. pulse of direct current. The light is presented as a 2°8′ field at approximately 13 ft.-L. Note that there is little agreement between these results and those of Motokawa as shown in Fig. 1. Where enhancement occurs at all it fails to conform to the specific wave-length curves that Motokawa has presented.

ference) than that of the first day. The average discrepancy in the two dark thresholds obtained before and after each light are also seen in Table 8. In

TABLE 8

VARIABILITY OF THE DATA OBTAINED IN EXPERIMENT II

(The differences in enhancement reported in this table are based on all 4 colors and 3 delay times, making a total of 12 differences going into each mean for each subject)

Subject	Differences Between Values Obtained Under the Same Conditions on Different Days			Mean Discrepancy (Absolute) Between Surrounding Dark Thresholds in Units of 2% Steps	Percentage of Dark Threshold Discrepancies of 5 Steps or Less
	Mean Difference (Absolute)	Mean Difference (Algebraic)	*SD*		
LAR	.087	+.053	.088	7.71	33%
SHH	.075	+.040	.090	5.17	58%
PMG	.050	−.045	.052	3.29	88%
JS	.027	−.008	.035	4.54	71%

the section of this report on evaluation of the LC method, similar measures of discrepancy were presented for *S*s LAR and SHH. In that study, however, the thresholds compared were immediately adjacent, i.e., without an intervening light threshold. Under those conditions lower discrepancies were found, i.e., 4.77 steps in the earlier study as opposed to 7.71 steps just reported for LAR, and 3.41 as compared to 5.17 for SHH. The increased discrepancies probably reflect the effects of the longer time interval between dark determinations. For *S*s PMG and JS, who did not take part in the earlier study, the mean discrepancy in the present study is less than five steps.

An important consideration in comparing these data to those of Motokawa is in the number of pairs of dark thresholds, preceding and following light, in which the discrepancy is less than 10 per cent, or approximately five steps. These figures also appear in Table 8. Motokawa discards data where the discrepancy between dark thresholds is greater than 10 per cent. It is evident that Motokawa would have rejected most of the data of *S* LAR, who showed the greatest enhancement values, but had only 8 out of 24 pairs of dark thresholds differing by five steps or less. On the other hand, 21 out of 24 of the enhancement points of PMG are based upon dark thresholds which vary by five steps or less, yet this *S* did not show consistently positive enhancement for any condition.

Conclusions with regard to enhancement as affected by delay time with a small central field. We may sumarize the results of Experiment II, then, by stating that (*a*) positive values of enhancement were not universally obtained in this experiment, (*b*) there was a marked tendency for higher enhancement values to occur with flashes of blue light than with white, green, or red when all flashes were of approximately equal photopic effectiveness, (*c*) only one subject (LAR) showed consistently positive enhancement values, and he was the most variable in his performance of all four of the *S*s, and (*d*) there is no consistent tendency for red light to yield the greatest enhancement at a delay time of 1 sec., green light at 2 sec., or blue light at 3 sec.

Experiment III. Enhancement as A Function of Intensity of the Preceding Flash of Light from A Small Central Field

The preponderance of very small values of enhancement in Experiment II suggests that some of the specific conditions of the experiment may not have been optimal for enhancement effects to occur. This is in spite of the fact that the conditions appeared to approximate those used in the studies by Motokawa. Accordingly, it was decided to vary some aspects of the stimulus in order to test the possibility that other conditions might be more favorable. Motokawa has reported that the degree of enhancement is positively related to the intensity of the preceding flash of light. It was therefore decided to use the three *S*s who showed relatively little enhancement in Experiment II, and find the degree of enhancement when intensity was varied. Red light and blue light were employed in Experiment III and three different intensities of each were presented. A 1-sec. delay time was used for the red and a 3-sec. time for the blue to favor a maximum degree of enhancement in accordance with the reports of Motokawa.

Procedure

Stimulating conditions. The conditions of Experiment III were similar to those of Experiment II. The flashes of

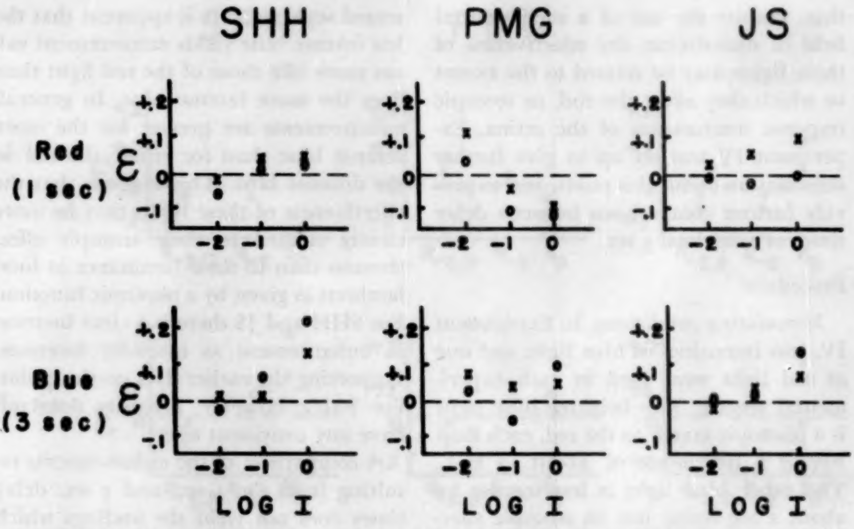


FIG. 7. Enhancement in relation to light intensity. Data for three different intensities of light, 2°8′ field, used in Experiment III.

light were seen as a 2°8′ field presented to the dark-adapted right eye of the *S*. Red (C) and blue (76) filters were used, and the variation in intensity of each was achieved by inserting 0.0, 1.0, or 2.0 log units of neutral density filter into the stimulating system.

During any one session, a single color was presented at each of the three intensities.

Experimental design. Three *Ss* served in this experiment for four sessions each. There were two sessions on each of the two colors, red and blue. During one of the sessions on each color, the intensities were presented in the order 0.0, 1.0, and 2.0, and during the other this order was reversed. The three *Ss* were those who showed least consistent enhancements in Experiment II.

Results. Figure 7 presents the data of Experiment III for each session for each *S*. The points marked with *x*s represent the first session on a given color, and *o*s the second session. It can be seen that *S* SHH shows an increased enhancement value with increasing intensity of light on all four sessions, with both blue and red light. The *S* JS has a clear intensity effect with blue light and on one session with red light. The *S* PMG, on the other hand, appears to have larger enhancement values for the lower intensity of red light, and the blue light has an irregular effect. Again in this study, the variability of the enhancement values under similar light conditions is high for all *Ss*. The variability of the dark thresholds preceding and following the light thresholds is of the same order as in Experiment II.

Experiment IV. Enhancement Produced By Matched Red and Blue Fields

Experiments II and III have yielded the information that blue light often produces considerably greater enhancement than does red of comparable photometric intensity. This finding suggests

that, despite the use of a small central field of stimulation, the effectiveness of these lights may be related to the extent to which they affect the rod, or scotopic response mechanisms of the retina. Experiment IV was set up to give further information about this point, and to provide further comparisons between delay times of 1 sec. and 3 sec.

Procedure

Stimulating conditions. In Experiment IV, two intensities of blue light and one of red light were used in each experimental session. The brighter blue light is a photopic match to the red, each flash having a luminance of about 13 ft.-L. The other blue light is less intense by about 2 log units; but its scotopic effectiveness is equivalent to that of the red light.

The light was presented as a 2°8′ field for two sec. The delay between the end of the light and the onset of electrical stimulation was either 1 sec. or 3 sec.; it was maintained at one or the other delay time throughout any given session.

Experimental design. Three *S*s participated in four sessions each for this experiment. In each of the four sessions, the two intensities of blue light and the red light were presented. For two of the sessions, the delay time was 1 sec. and for the other two it was 3 sec. A single session began with one intensity of blue light, followed by red light, and ended with the other intensity of blue. The intensity of the initial blue light was varied in an ABBA order over the four sessions, while the delay times, 1 sec. and 3 sec., were alternated.

Results. Figure 8 presents the enhancement values obtained in each session. As before, the first session is indicated by *x*s and the second by *o*s. The results for the 1- and 3-sec. delay times are presented separately. It is apparent that the less intense blue yields enhancement values more like those of the red light than does the more intense blue. In general, enhancements are greater for the more intense blue than for either the red or the dimmer blue. This suggests that the effectiveness of these lights may be more closely related to their scotopic effectiveness than to their luminance in footlamberts as given by a photopic function. For SHH and JS there is a clear increase in enhancement as intensity increases, supporting the earlier data on this point. For PMG, however, intensity does not have any consistent effect.

A comparison of the enhancements resulting from the 1 sec. and 3 sec. delay times does not yield the findings which would be predicted by Motokawa. That is, there is no consistent tendency for enhancement to be relatively greater at 3 sec. for blue light and at 1 sec. for red. The data appear to be slightly less variable with a 1-sec. delay than with a 3-sec. one.

The variability of the dark thresholds in this study is similar to that obtained earlier. For two *S*s the average discrepancy between dark thresholds preceding and following the light threshold is slightly less than five steps, or 10 per cent, whereas this discrepancy is approximately seven steps for the third *S*, JS.

Experiment vs. Enhancement Following Flashes of Light from a Large Field

The results of Experiments II, III, and IV have shown that blue light usually produces a greater enhancement of electrical sensitivity than does green or red light of equal photometric luminance. This has led to the supposition that the enhancement due to a flash of light may be governed by its ability to stimulate the rod or scotopic receptor system. That

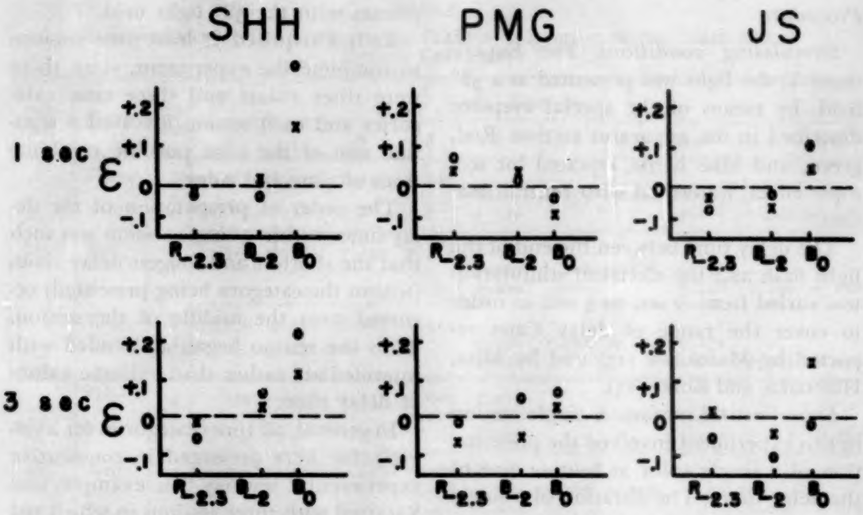


FIG. 8. Enhancement produced by matched red and blue fields. The red light, $R_{-2.3}$, has approximately the same luminance (13 ft.-L.) as the brighter blue light, B_0. The scotopic effect of the red is approximately that of the dimmer blue light, B_{-2}. Results of Experiment IV with a 2°8′ field and delay times of 1 sec. and 3 sec.

this should be true for stimulation by a small, central field of light may at first appear to be unlikely. Work with the human electroretinogram has clearly shown, however, that scotopic effects may arise in this way. Indeed it is found that it is difficult, if not impossible, to obtain any electrical responses from the stimulation by light of small central areas (Adrian, 2, 3; Riggs and Johnson, 24). Such responses as do occur in the human eye under these conditions have been shown by Boynton (4) to originate primarily from the action of stray light on peripheral scotopic receptors. These facts suggest that the peripheral regions of the retina occupy a preferred location, electrically, so that diffuse electrical stimulation of the eye by large electrodes has primarily peripheral effects.

If the enhancement resulting from small-field stimulation is due primarily to the action of stray light on peripheral receptors, then it should be true that an even more effective means of securing enhancement would be to extend the size of field so as to provide a more direct stimulation of the rod receptors. Furthermore, most *Ss* report that the phosphenes aroused by weak electrical stimulation are not localized in the central so much as in the peripheral field of view. It seems appropriate, therefore, to use large-field stimulation in order to affect by light those regions of the retina that appear to be affected by electrical stimulation.[9]

[9] We have found that when the intensity of the large field is reduced to near-threshold levels it becomes impossible for the *S* to distinguish between the "phosphenes" produced by photic and electrical stimuli, provided that the photic stimulation is in the form of a large field. Either form of stimulus results in a vague, colorless cloud of light.

Procedure

Stimulating conditions. For Experiment V, the light was presented as a 38° field, by means of the special eyepiece described in the apparatus section. Red, green, and blue lights, equated for scotopic effect, were used with central fixation.[10]

The delay time between the end of the light flash and the electrical stimulation was varied from .2 sec. to 4 sec. in order to cover the range of delay times reported by Motokawa (15) and by Mita, Hironaka, and Koike (13).

Experimental session. A single session in this experiment involved the presentation of a single color at four or five of the delay times. The duration of a single session was limited to 1½ to 1¾ hours, and this factor determined the number of enhancement values that could be obtained. The delay times were divided into three categories. Category I included the short times (0.2, 0.4, 0.6, 0.8, and 1.0 sec.); category II included medium times (0.8, 1.0, 1.25, 1.50, and 2.0 sec.); and category III included times in integral seconds (1, 2, 3, and 4 sec.). On a given session the times from one of these categories were presented. Since the categories overlap, we have obtained several determinations for some of the delay times but only single determinations for others.

Experimental design. Four *S*s participated in this experiment. Two of them, LAR and SHH, had already observed in the small field experiments. The other two had had no experience with the small field, but were given preliminary training in the observations of phosphenes with the 38° light field.

Each *S* required at least nine sessions to complete the experiment, since there were three colors and three time categories and each session involved a separate one of the nine possible combinations of time and color.

The order of presentation of the delay times within a single session was such that the shortest and longest delay times (within the category being presented) occurred near the middle of the session. Thus the session began and ended with intermediate rather than extreme values of delay time.

In general, all times categories for a single color were presented in consecutive experimental sessions. For example, one *S* started with three sessions in which red light was used, followed by three of green and three of blue. The order of presentation of colors and categories is included in Table 9 in the results section. The time category for the first session of a given color was randomized, as was the order of colors presented.

Results

Effects of delay time on enhancement. Table 9 shows the principal results of Experiment V. It is seen that the enhancement values are negative for short delay times for all *S*s. Longer delay times yield predominantly positive enhancement for two of the *S*s, but for the other two the enhancement values are essentially zero. In Fig. 9, an attempt is made to show these findings graphically. The number of experimental points is too great to be shown individually in this figure. Accordingly, all the ε values referring to the same condition of delay time, *S*, and color have been combined by averaging to a single value on the graph.[11]

Our major conclusion from this ex-

[10] Equal scotopic effectiveness was achieved for the *C*, *G*, and 76 filters, designated in this paper by *R*, *G*, and *B*, by the use of neutral density filters. As used here, the scotopic effectiveness is approximately equal to that of white at 3 ft.-L.

TABLE 9

ENHANCEMENT VALUES (ε) FOLLOWING FLASHES OF LIGHT FROM THE LARGE FIELD USED IN EXPERIMENT V

Subject	Color	Session	Delay Time (sec.) .2	.4	.6	.8	1.0	1.25	1.50	2.0	3.0	4.0
	Green	4	−.251	+.017	+.076	+.140						
		5					+.117	+.153	+.077	+.165		
		6					+.126			+.165	+.095	+.126
SHH	Red	3	−.326	+.111	+.155	+.311						
		1					−.007	+.218	+.178	+.176		
		2					+.229			+.148	+.169	+.118
	Blue	8	−.270	+.177	+.205	+.313						
		9					+.256	+.222	+.291	+.271		
		7					+.270			+.201	+.298	+.256
	Green	3	−.149	−.038	+.012	+.009	+.017					
		2				−.016	+.032	+.017	−.036	+.028		
		1					+.031			+.008	−.012	+.025
MC	Red	5	−.342	−.075	−.057	−.086	−.018					
		9				−.058	−.009	−.062	−.046	−.044		
		4					−.014			−.013	−.039	+.010
	Blue	7	−.375	−.121	−.246	−.006	−.084					
		8				+.019	+.083	−.043	−.011	−.036		
		6					+.030			.000	−.032	−.040
	Green	5	−.364	−.210	−.175	−.126	−.114					
		6				−.078	.000	−.070	−.021	+.017		
		7					−.086		−.021	−.029	−.077	−.116
CJW	Red	10	−.274	−.253	−.131	−.135	−.112					
		9				−.078	−.056	−.065	−.057	−.081		
		8					−.074	+.003		+.128		
		2					−.032			+.011	+.017	+.023
	Blue	3	−.211	−.170	−.078	−.046	−.057					
		4				−.004	−.045	−.022	−.017	−.043		
		1					−.028			+.048	+.032	+.042
	Green	10	−.061	+.009	+.106	+.240	+.182					
		11				+.143	+.125	+.152	+.172	+.225		
		3					+.148			+.019	+.185	+.024
LAR	Red	8	−.171	−.049	+.102	+.159	+.165					
		9				+.275	+.213	+.178	+.112	+.193		
		2					+.119			+.084	+.111	+.057
	Blue	5	−.157	+.169	+.242	+.304	+.206					
		7				+.341	+.247	+.194	+.309	+.225		
		6				+.269	+.096	+.184	+.124			
		1					+.304			+.236	+.188	+.262
		4					+.280			+.209	+.242	+.255

[11] The averaging has been done for convenience in presenting the results, and it must be realized that there is some variability in the points going into these averages. The individual points are found in Table 9. These points support equally well our conclusions with regard to enhancement as a function of delay time.

periment is that beyond about one second of delay time there is little relationship between delay time and degree of enhancement. This conclusion applies to each of the colors used; i.e., there is no apparent "crest time" as a function of

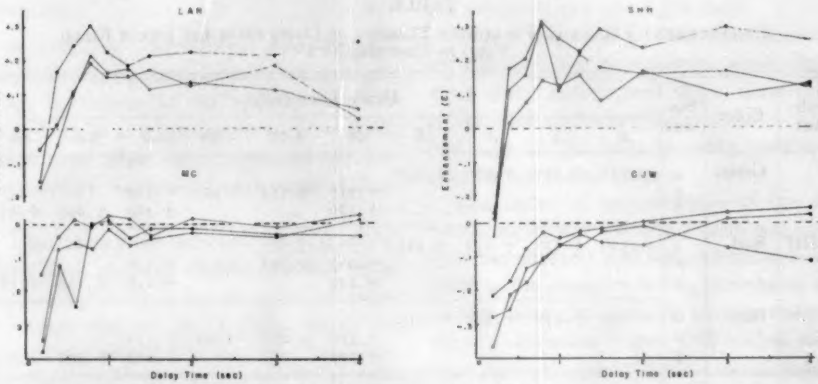


FIG. 9. Enhancement as a function of delay time for blue (•), green (o), and red (x) lights of equal scotopic effectiveness in Experiment V. The light is present as a 38° field whose scotopic effectiveness is similar to that of white light at 3 ft.-L. Compare with Motokawa's results in Figure 1. Note that enhancement is clearly present in but two out of the four subjects; and these two fail to conform to the pattern predicted by Motokawa. All four subjects, however, show clear evidence of reduced electrical sensitivity immediately following the light flash.

the wave length of the light. *There are no marked differences in effect among the three colors used here.* As before, however, the blue light does appear to have a greater effect than the red or green, especially in the cases of the two *Ss*, LAR and SHH, who showed large positive enhancements. This is in spite of the fact that the blue light is much less bright, in terms of photopic luminance, than the other colors. Since the three colors are approximately equal in their scotopic effectiveness, it appears to mean that the degree of enhancement is approximately what one might predict from a rod-receptor mechanism, but that blue is slightly more effective than would be expected.[12]

[12] This finding may perhaps be the result of Rayleigh scattering which, in the case of the human electroretinogram (Boynton, 4) has often given the appearance of excess blue sensitivity. Blue light is very effectively scattered by the optic media, so that it exerts a disproportionate influence on functions involving the extreme periphery of the eye.

Data on threshold variability. As in the previous studies, we have measured the number of steps separating the two reference thresholds used to compute the enhancement effect of each light. The number of such pairs for each *S* in Experiment V is from 36 to 51. For all *Ss* the average discrepancy is less than five steps, or approximately 10 per cent. Table 10 presents these averages, together with the percentages of pairs in which the discrepancy was five steps or less.

TABLE 10

AVERAGE DISCREPANCY BETWEEN REFERENCE THRESHOLDS PRECEDING AND FOLLOWING A LIGHT THRESHOLD

(in 2 per cent step units)

	LAR	SHH	CJW	MC
Average Discrepancy	3.33	4.64	4.06	4.15
N	51	36	40	40
Percentage of Discrepancies of 5 Steps or Less.	79	64	70	75

The variability in dark thresholds in this experiment was in general smaller than had been found in the earlier studies. The reasons for this are not clear. Two of the Ss were highly experienced and two were relatively inexperienced. It is of interest that most of the pairs of reference thresholds (from 64 per cent to 79 per cent of them in the various Ss) had small enough discrepancies so that they would have been accepted as valid by Motokawa's criterion of reproducibility within 10 per cent.

Experiment VI. Enhancement as a Function of Intensity of Light from a Large Field

Experiments II, III, and IV demonstrated that with some Ss the degree of enhancement is positively related to intensity of light, as Motokawa has reported with a small, central field of light. Experiment V has demonstrated high values of enhancement for two of the four Ss when large-field stimulation is employed. Experiment VI is one in which a large field of white light is presented at three different levels of intensity. The aim of this experiment was to maximize the enhancement effect by utilizing a large field of light, and to study the influence of delay time and intensity on enhancement under these conditions.

Procedure

Stimulating conditions. All the data included in this section were obtained with the large (38°) field of light preceding the electrical pulse. Three intensities of white light were used. The middle intensity was the scotopic equivalent (with 2.6 log units of neutral density filter) of the colors presented in Experiment V. Its photometric luminance was approximately 3 ft.-L. The other two intensities were two log units above and below that value. Each flash of light was followed, as before, by an electrical test stimulus at a delay time ranging from 0.2 sec. to 4 sec.

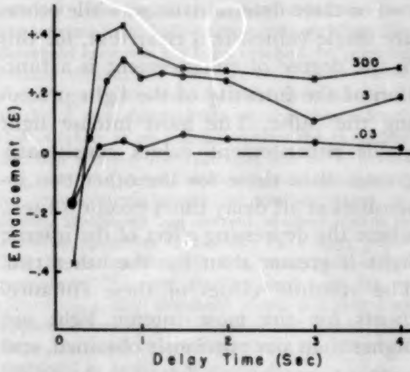


FIG. 10. Enhancement as a function of delay time for white lights of approximately 300, 3, and 0.03 ft.-L. luminance. Subject LAR, Experiment VI. Two other subjects failed to show consistently positive enhancement under the same conditions.

Experimental design. The design of Experiment VI was similar to that of Experiment V. In a given session, only one intensity of white light was used, at various delay times. Three Ss were used.

Results. As in previous experiments the thresholds for electrical stimulation were found to be high immediately following each flash of light. In other words, the value of ε was negative for delay times below about one sec. With longer delay times one S (LAR) showed positive values of ε as in earlier experiments. Two other Ss failed to show any positive enhancement effects.

Figure 10 presents the time course of enhancement for three intensities of white light for the one S whose electrical thresholds are markedly affected by the lights of various intensities. As in the previous experiment, some of the points on these curves represent the averages of

two or three determinations, while others are single values. It is clear that, for this *S*, the degree of enhancement is a function of the intensity of the light preceding the pulse. The most intense light yields enhancement values consistently greater than those for the other two intensities at all delay times except 0.2 sec., where the depressing effect of the intense light is greater than for the other two. The absolute values of these enhancements for the most intense light are higher than any previously obtained, and appear to reach a maximum in the neighborhood of one sec. after the flash. Some tendency toward the one-sec. maximum is also shown at the middle intensity of white light in this figure and in the most intense blue light of Fig. 9.

Experiment VII. Enhancement Produced by Large Fields of Colored Lights of Equal Luminance

Intensity of white light has been shown to determine the degree of enhancement in a *S* who readily shows enhancement effects. For colored lights it is clear from the data of Experiments II, III, IV, and V that this intensity should be evaluated not in photometric units of luminance but rather in terms of the effectiveness of the light for stimulating the scotopic system of the eye. Experiment VII is one in which this conclusion is further verified by the use of colored lights of approximately equal photopic luminance.

Experiment VII consisted of presenting blue, red, and green lights whose intensities were equivalent, photopically, to a white light of about 0.2 ft.-L (with 3.6 log units of neutral density filter). These lights were followed by electrical stimulation at 1-, 2-, 3-, and 4-sec. delay

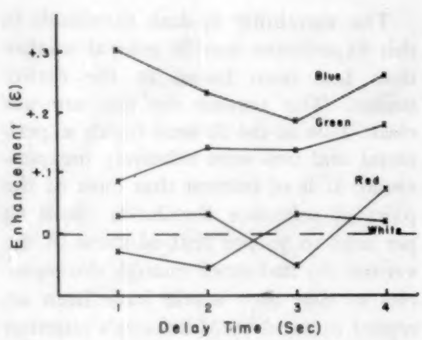


FIG. 11. Enhancement as a function of delay time for blue, green, red, and white lights of approximately 0.2 ft.-L. luminance. Subject LAR, Experiment VI. A second subject also showed greater enhancement for blue than for the other colors, but failed to show consistent effects in relation to the variable of delay time.

times. From the results of Experiments II, III, IV, and V it would be predicted that these lights, though of equal luminance, would yield different amounts of enhancement. Thus blue light, because of its relatively greater effectiveness for arousing the peripheral scotopic system, would be expected to produce greater enhancement than green, and green greater than red.

Figure 11 presents the results for the one *S* (LAR) who showed consistent enhancement effects. As predicted, the blue light is most effective in enhancing the electrical threshold, green light is less effective, and white and red lights are least effective. The points on these curves represent single determinations, and the three curves were obtained on consecutive days. The curve for white light was obtained approximately two weeks later. The data for another *S* were more variable but confirmed the fact that the blue light was the most effective of the colors used.

Effects of Electrical Stimulation at Subthreshold Intensity Levels

The Concept of Multiple Thresholds

A central concept in the thinking and experimentation of Motokawa is that of multiple thresholds. This concept is to the effect that several electrical thresholds corresponding to the several fundamental response mechanisms of the retina may manifest themselves at once in the responses of the *S.* No provision for such a phenomenon is made in the usual psychophysical experiments. In fact, there appear to be certain logical difficulties implicit in the concept. Nevertheless, the stress laid on multiple thresholds by Motokawa and the revolutionary nature of this idea make it important that they be given serious consideration in relation to our procedure and results.

Specifically, *Motokawa assumes that several electrical thresholds may exist at any one time, one threshold for each of the fundamental response mechanisms affected by the preceding flash of light.* Of these multiple thresholds the true one is assumed to be the lowest, i.e., the one below which no phosphene is ever reported by the *S.* Motokawa (20) has insisted that great care is necessary to attain the lowermost or true threshold. In his words, "Trained Os can easily pass apparent thresholds and reach the true threshold, but untrained Os stop at one of the apparent thresholds, because they cannot discriminate sufficiently slight phosphenes from the background." An inexperienced experimenter may fail to continue presenting the stimuli in the descending series until the lowermost threshold is attained.

In order to avoid the danger of stopping the determination at one of the apparent thresholds and not attaining the true one, Motokawa (21) has suggested the following procedure. When the threshold criterion has been reached, he presents further comparison pairs at an intensity level about 5 per cent lower than the threshold level. If the *S* can discriminate at this lower level, this is taken as an indication that the threshold attained was not the true one, but an apparent one, and the determination is continued until no lower discrimination is possible. More recently, Motokawa has devised another means of avoiding apparent thresholds. In a 1955 paper (22) he makes the following statement of his procedure: "In our routine work, we try to determine a true threshold alone, skipping over apparent ones by graduation of voltages in gross steps, but not forgetting that the obtained threshold is really a true one."

There appear to be certain logical difficulties in the concept of multiple thresholds. Let us assume that the blue response mechanism, for example, accounts for the lowermost or "true" electrical threshold and the red response mechanism has a somewhat higher electrical threshold under certain experimental conditions. Does this not mean that an electrical stimulus whose intensity is equal to that of the red response threshold will stimulate even more strongly the blue response mechanism? In other words, is it not difficult to conceive of a psychophysical relationship showing anything but a decreasing frequency of "yes" responses as stimulus intensity goes down, even though several different response mechanisms may be affected simultaneously?

In our own experiments the effects of light have been specified in terms of the change that the light produces in the threshold for electrical stimulation of the eye. Each threshold has been determined by the LC method as specified above in the section on general procedure. It must be emphasized that this method has been rigidly imposed in all cases, and that equal log steps have always been

used in locating the threshold. This practice obviously differs from the one described by Motokawa in the above quotation, where he advocates the use of steps of differing size for various portions of the descending series of stimuli.

In terms of the concept of multiple thresholds, it must be supposed that the thresholds we have determined, following flashes of light, are not necessarily the "true" thresholds but are sometimes the higher ones characteristic of less sensitive response mechanisms. Therefore one could regard our data as composed of a mixture of true and apparent thresholds. If so, only the true thresholds would represent the individual color response mechanisms that Motokawa has described in terms of their time course. In spite of these considerations, we have conducted our regular threshold determinations according to the rigid protocol described above. We have been unwilling to employ gross steps in any portions of the psychophysical procedure used in determining the threshold and have always ended the determination at the criterion intensity. We agree with Motokawa that his arbitrary use of unequal steps may be a crucial factor in the attainment of his specific wave-length effects.

Rather than to make allowance for possible multiple thresholds in our regular experiments by departing from rigid protocol, we have preferred to conduct a series of control experiments in order to evaluate the status of multiple thresholds. There appear to be two consequences of the multiple threshold concept that can be tested experimentally. First, multiple thresholds should not appear in the "dark" or "reference" series, but should readily be found in the "light" series, where there are differential effects of the light on the red, green, and blue response mechanisms of the eye. Second, a function relating frequency of seeing to intensity of electrical stimulation should not rise progressively in "light" series, but should exhibit a series of maxima, one for each of the multiple thresholds characteristic of the fundamental response mechanisms. Experiments VIII and IX are designed to test these two predictions of the multiple threshold concept.

Experiment VIII. Extension of the LC Method to Subthreshold Levels

Procedure. Experiment VIII is one in which a flash of light is chosen for which multiple thresholds might well be predicted. The usual LC method is employed to find a threshold and then stimulation is continued to lower and lower stimulus intensities. In this way it is possible to find the extent to which phosphenes are aroused by stimuli that are below the usual threshold. By the use of suitable criteria it is possible to observe the number of steps by which the stimulus intensity can be lowered below the usual threshold in order to locate new "thresholds" of still lower intensity. Finally the same procedure is followed in "dark" series without any flash of light. The extent of the subthreshold range can then be compared for the light and dark conditions.

Stimulating conditions. For the light condition in this experiment, blue light of moderate intensity (76 filter with 1.0 log unit of neutral density) was used for all *Ss*. The time between the end of the two-sec. light flash and the onset of the electrical pulse was 1 sec. for three *Ss* and .5 sec. for the fourth, LAR. These times and wave length were selected as favorable for the existence of multiple thresholds, as described by Motokawa with reference to one of his published figures (Figure 2 in reference 20). The field size

was 2° 8′ for three *Ss*, and 38° for the fourth (CJW). The differences in experimental conditions in these experiments result from the fact that they are control experiments for certain of the main experiments reported above.

Subjects. Four *Ss* served in this experiment. Three of them, LAR, PMG, and SHH were highly experienced *Ss* who had participated in the crest time study. These three *Ss* saw the 2° 8′ field in the light condition of this experiment, as they had in the crest time study. The fourth *S* in this experiment, CJW, had participated only in previous experiments in which the large 38° field was used, and viewed that field in the present experiment.

Psychophysical procedure. In order to attempt to find multiple thresholds, an extension of the comparison stage of the LC method has been introduced. This involves establishing a new criterion for ending the threshold determination, one which gives the *S* an opportunity to discriminate at intensities lower than that at which he meets the usual threshold criterion. The procedure is begun with the limits stage, and continues through the comparison stage as before. When the original threshold criterion is met, however, the current is reduced by one step and the comparison procedure is continued. Each time that the *S* correctly identifies the position of the test stimulus, the intensity is reduced. If he fails to identify the test stimulus three times in a row, or makes two errors at the same intensity, he is said to have reached a second "threshold" by virtue of meeting again the usual criterion for threshold. The condition for stopping the determination in the extended LC method is that the *S* reach this original criterion on two *consecutive* intensity steps. Furthermore, the second of these two steps must be at least five intensity steps below the step at which he *first* met the criterion. At this point, one further comparison pair is presented. The intensity of this last comparison pair is three steps below that step on which he met the criterion for the second consecutive time. In order for the determination to be stopped, the *S* must fail to respond correctly on this final comparison pair. If he does respond correctly to this pair, the intensity is increased by two steps, i.e., to a level one step below his last "threshold," and the comparison procedure is continued until he again meets the criterion on two consecutive steps and fails on a pair three steps lower.

By the use of this extended LC method, no threshold determination is terminated until the *S* has had an opportunity to judge comparison pairs at least five steps below his original threshold. Motokawa states that a safeguard against stopping the determination at a falsely high threshold is to present a comparison pair which is well below the threshold. If the threshold were a false one, this lower pair would presumably be judged correctly, indicating to the experimenter that he should continue lower in order to find the "true" threshold. Our extension of the procedure accomplishes Motokawa's aim in a standardized fashion and at the same time allows us to state the extent to which the *S* can respond correctly at levels below his original threshold.

Experimental design. This experiment consisted of two identical sessions for each of the four *Ss*. Each session was begun with a preliminary LC determination of a dark threshold, after 10 minutes of dark adaptation. This threshold was determined by the ordinary procedure described above, with no extension of the comparison series. After 20 minutes of dark adaptation, the first of four

TABLE 11

A. Total Number of Steps Between Original and Final Threshold

	Dark Condition					Light Condition				
	1	2	3	4	Total	1	2	3	4	Total
LAR	6	19	15	18	58	9	5	6	5	25
SHH	7	11	17	13	48	10	5	5	5	25
PMG	9	10	14	9	42	9	5	7	11	32
CJW	10	9	29	9	57	13	8	9	10	40
Total					205					122

B. Number of Steps Correctly Judged Between Original and Final Threshold

	Dark Condition					Light Condition				
	1	2	3	4	Total	1	2	3	4	Total
LAR	3	15	6	7	36	4	3	4	2	13
SHH	4	8	13	7	32	5	1	2	2	10
PMG	6	4	8	4	22	1	0	4	8	13
CJW	6	4	19	5	34	9	7	5	5	26
Total					124					62

extended threshold determinations was begun. The first and third of these were dark, or reference thresholds, and the second and fourth were light thresholds.

Results. The results of this experiment are of interest chiefly as comparisons of the dark and light conditions. Two such comparisons are presented. Both are based upon the responses made to stimuli *below* the level of the original threshold. That is, interest here is centered upon what happens during the special extension of the comparison stage of the LC method.

First, let us consider the number of two per cent steps between the original threshold and the termination of the extended threshold determination. It will be noted that the minimum number of steps between these two criteria is five, since the extended series was never terminated until at least five steps below the first threshold had been presented. Second, we may note the number of steps *correctly* judged between the original and final thresholds. No minimum number of steps exists for this measure, since the *S* may make no correct judgments after his original threshold has been reached. This measure, then, reflects the success with which the *S* was able to discriminate at intensity levels below that which was called threshold in the earlier experiments. The data in Table 11 include both of these measures. Because the conditions (field size, delay time) differed slightly among the four *Ss*, individual data are presented in Table 11. All eight thresholds for any given *S* however were obtained under identical conditions. Both measures given in Table 11 show that *Ss* are often able to discriminate phosphenes from blanks at intensity levels below the original threshold in both the light and dark conditions. But in no case does the light condition exceed the dark condition in the number of successful discriminations. Instead, the dark condition seems to favor such discriminations, yielding about twice as many steps, when all *Ss* are combined, for both measures. This result is in contrast to the

prediction of Motokawa (22) for the multiple threshold effect. His prediction is that of a more abrupt transition from positive to negative responses in "dark" determinations as opposed to "light" determinations.

Experiment IX. Employment of the CS Method with Small Steps of Intensity Above and Below the Threshold

The results of Experiment VIII have indicated that phosphenes are sometimes aroused by stimuli below the usual threshold, but that this is not brought about in any unique fashion by the aftereffects of flashes of light. The conventional concept of a threshold demands, in fact, that some positive responses be observed when stimuli of subthreshold intensity are given. Accordingly, Experiment IX was conducted to quantify the relationship between the frequency of positive responses and the intensity of stimulation over a wide range of subthreshold and suprathreshold intensities.

Procedure. The method of constant stimuli was used in Experiment IX. Nineteen intensities of electric current were presented 20 times each. These intensities differed by steps of two per cent, as was true of the steps used in the LC method. A blank stimulus was also presented 20 times, making a total of 400 presentations. A rest period of about one minute followed each 40 presentations. A random order of 300 stimuli, including each intensity 10 times, was presented twice in opposite directions. The *S* responded to each stimulus by saying "yes" or "no" and the experimenter made no comments except to identify the blank stimuli after they had occurred.

A 2-sec. blue light (76 plus 1.0 log units N. D.) preceded each electrical stimulation by a delay time of .5 sec. As in all of the experiments in which light

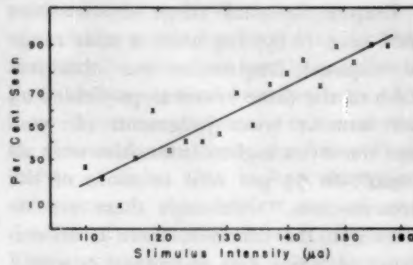


FIG. 12. Percentage of "yes" judgments for the appearance of phosphenes in relation to intensity of the stimulating current.

Method of constant stimuli with 2 per cent steps. Subject LAR, Experiment IX. This experiment was attempted with two additional subjects. Their data failed to satisfy the usual criterion of 75% or more judgments of "seen" at the high end and 25% or fewer at the low end. Presumably this is a consequence of the length of the experiment (2½ hours) and the small size of step (2%), factors that render the experiment an unusually arduous one for the subject.

was presented, 15.3 sec. separated successive stimulations. The small (2° 8′) field of light was used, with central fixation.

The session was begun with a preliminary threshold determination by the LC method without light, followed by another preliminary LC threshold with the same intensity and delay time as was used in the CS determination. The CS determination was begun at approximately 30 minutes after the *S* entered the dark room, and it took approximately two hours to complete the series of stimulus presentations.

Results. Figure 12 presents the constant stimulus function for *S* LAR, plotted on probability paper. The abscissa is log intensity of current and the ordinate is per cent seen plotted on a scale of probability. The blank stimulus was never reported as seen during the 20 presentations. The straight line has been fitted to the points by the method of least squares.

Despite the small range of intensities used here (0.157 log unit), a wide range of response frequencies was obtained. Each of the three lowest steps yielded 25 per cent or fewer judgments of "yes" and the seven highest intensities were all "seen" on 75 per cent or more of the presentations.[18] Although there are reversals in the function, there is no evidence of major dips and peaks, as would be predicted by the multiple threshold hypothesis. Rather, the points follow the prediction of a Gaussian function, with some variability which too would be predicted with such small intensity differences as 2 per cent between steps.

It is concluded, then, that the data of Experiments VIII and IX offer no support for the concept of multiple thresholds as outlined by Motokawa. Responses to subthreshold intensities of current are indeed observed, but the percentage of positive responses appears to exhibit an approximately Gaussian relationship to the log of the stimulating current.

Summary of Results

A brief summary of the results of these experiments is as follows:

Experiments have been conducted in which the human eye was stimulated electrically by brief square-wave pulses. Three or four highly trained *S*s were used in each experiment. The *S* judged the appearance or nonappearance of a phosphene in response to the pulse. A psychophysical method developed by Motokawa was used to determine the threshold for the electrical stimulation. This method involves successive stimulus presentations in a descending series of intensities, as in the method of limits, followed by paired comparisons of blanks with successively weaker stimuli. When conducted under rigidly prescribed conditions this limits-comparison procedure can be used to measure changes in electrical sensitivity following flashes of light in the dark-adapted eye. More conventional psychophysical methods appear to be more reliable for determining electrical thresholds but are too time consuming to be used in extensive series of threshold dominations.

Immediately following a flash of light the eye is relatively inexcitable by electric current, but within less than one second after the light goes off the excitability rises to a normal or supranormal level. Supranormal excitability, or enhancement, is not found in some *S*s but is clearly present in others. A study of various colors, areas, and intensities of stimulation has led us to conclude that the degree of enhancement depends largely on the extent to which the light has stimulated the rod, or scotopic receptor mechanism, of the eye. The enhancement effect often persists for several seconds after a flash of light. We have not found any clear peak, however, in the time course of such enhancement, and we have not found the specific wave-length effects reported by Motokawa for this time course. Certain factors of experimental procedure are believed to account for this discrepancy in results.

Discussion

The principal purpose of these experiments has been to evaluate the method of electrical stimulation of the eye as a tool for studying the mechanism of human color vision. After a general evaluation of methods of determining electrical thresholds (Experiment I), our primary

[18] Attempts to obtain a constant stimulus function with 2 per cent steps, under similar light conditions, were made with two other *S*s PMG and SHH. In both cases, however, the attempts were unsuccessful in that the range of intensities was not large enough to obtain an appropriate range of percentages seen.

concern was to attempt to verify the results reported by Motokawa for the enhancement of electrical excitability by flashes of lights of various wave lengths. Later we were led to a new series of experiments in which we explored the role of the scotopic or rod response mechanism in the enhancement of electrical sensitivity.

Comparison With the Motokawa Experiments

Experiments II, III, and IV were designed to follow closely the procedures reported by Motokawa. Red, green, blue, and white lights were used with central fixation on a small field with luminances within the range that Motokawa had reported as effective. Duration of the light flash was two seconds, the value most often used by him, and delay times of 1, 2, and 3 sec. were interposed between the flash and the 0.1-sec. square-wave test pulse of direct current through the eye. Three or four carefully trained *S*s were used and adequate periods of dark adaptation and rest were provided.

Threshold determinations were made according to the design developed by Motokawa. A descending method of limits was followed by a comparing procedure in which the final threshold was ascertained by the *S*'s failure to distinguish blanks from electrical pulses. Despite these similarities, we have not claimed that Motokawa's experiments have been exactly duplicated in our laboratory. The principal difference between our experiments and his appears to be in the application of the procedure in the daily routine of threshold determinations.

With such a high degree of similarity in experimental conditions we should certainly expect our own results to resemble those of Motokawa in all important respects. Nevertheless the extent of such agreement has been very limited, and may be described briefly as follows: First, we have indeed found some *S*s who show impressive amounts of enhancement of electrical sensitivity resulting from flashes of light. The highest degree of enhancement seen under any of our conditions was one of about 0.4 log unit. This represents a drop in electrical threshold to approximately 40 per cent of its original value. In most cases, however, much smaller values of enhancement were obtained. In fact, nearly half of our *S*s failed to show any consistent enhancement effects under any conditions. We have not found any explanation for these wide individual variations. Second, we have confirmed rather closely the early time course of enhancement, reported by Motokawa and his co-workers for the first half-second after the light goes off. Third, we have found, in some *S*s, a clear relationship between the amount of enhancement and the intensity of the light flash that produced it.

While we have confirmed the existence of enhancement of electrical sensitivity by light, we have not been able to make use of this phenomenon as a tool for the study of color vision. This is because we have not obtained any differences among the various colors of light with regard to their aftereffects on electrical sensitivity of the eye. Motokawa's impressive series of studies, purporting to give an exact description of the fundamental response curves for human color vision, is based upon these specific aftereffects of various colors. Motokawa's consistency in obtaining these effects is in marked contrast to our own negative results, obtained under a variety of experimental conditions.

Differences in the routine of threshold determinations. We have corre-

sponded with Professor Motokawa about our negative findings with respect to specific wave-length effects. His opinion is that procedural differences are important in accounting for the differences in results obtained in the two laboratories. Motokawa has sent us sample protocols from one of his experiments, in order to illustrate the differences between his routine procedure and ours. With Motokawa's kind permission, we have reproduced one of these protocols as Table 12. We believe that it contains a more detailed description of his procedure than has appeared previously.

The protocol describes an experiment in which enhancement was measured following a flash of red light at various delay times. The typical time course was found, with the greatest enhancement occurring at a delay time of one second. The *S* was one of Motokawa's highly trained observers. We have taken the liberty of presenting Motokawa's protocol in such a way that the vertical position of each entry corresponds to the intensity of stimulation. The intensity values of the presentations are indicated on the left of the table, in units of electrical resistance in ohms. As the number of ohms increases, the stimulating voltage decreases.[14] Spaced out in this way, the values clearly indicate the differences in step size which Motokawa has used in arriving at his thresholds. The columns headed $R_{0.5}$, R_1, R_2, and R_3 contain threshold determinations at delay times of 0.5, 1, 2, and 3 sec. after the cessation of a 2-sec. flash of red light. The columns headed R_0 indicate reference threshold determinations in which no light was present. The order of the columns indicates the order of threshold determinations in this experiment. Within each column are notations of the *Ss'* responses. An *o* in the body of the table is used to indicate that a phosphene was seen by the *S*, and an *x* indicates that it was not seen. The letters *w* and *vw* indicate the *S*'s report that the phosphene was weak or very weak. The notation *com* indicates the intensity at which the comparison stage of the procedure was demanded by the *S*. At all subsequent intensities, the comparison procedure was used. After the threshold was reached, several further comparison pairs were presented, in order to ensure that the threshold obtained was the "true" one, and not an apparent one. This is indicated by a double *x*; and all further single *x*s indicate that the *S*'s response was "I don't know."

[14] Motokawa's circuit for electrical stimulation can be found in reference 18.

The concept of multiple thresholds, as outlined in a previous section of this paper, has led Motokawa to use gross steps in the initial phase of the determination of a threshold. Furthermore, in the determinations in which light was used, he employed gross steps in order to skip over the "dark" thresholds, i.e., the intensity values which had yielded thresholds with no light present. This procedure, also described by Motokawa in a recent publication (22), was instigated to avoid apparent thresholds and to ensure obtaining the true threshold.

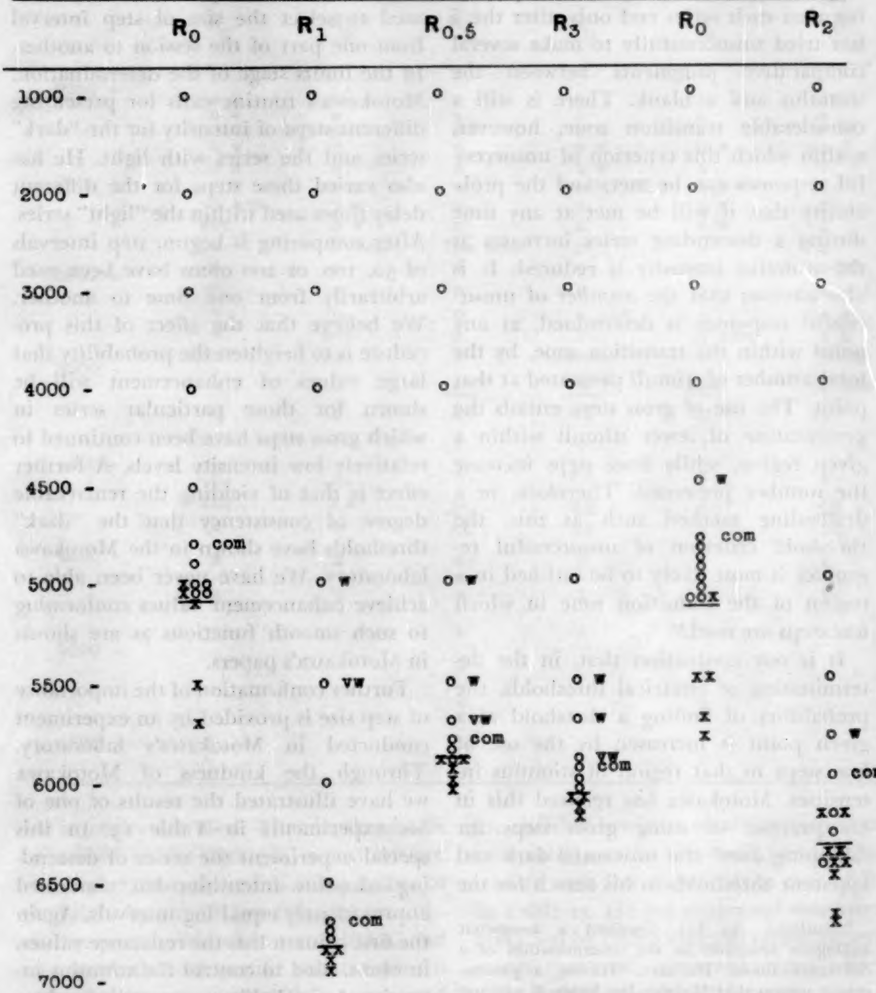
In Experiments VIII and IX, some consequences of the multiple threshold concept were tested. The weight of the evidence appeared not to support this concept, but instead to be consistent with the usual view that a threshold is a point statistically defined within a transition zone of stimulus intensities over which the probability of a given response changes gradually from low to high.

The effect of step size on a threshold. Conventional treatments of psychophysics make no provision for multiple thresholds, assuming instead that a single threshold can be found by the use of equal steps along a continuum of stimulus intensities. In a descending series there is no exact point at which the *S* changes his judgment from "seen" to "not seen." Rather there is a transition zone from suprathreshold regions in which judgments of "seen" predominate, to subthreshold regions in which judgments of "not seen" become more and more numerous. The threshold is ordinarily defined statistically as that stim-

TABLE 12

ADAPTATION OF A PROTOCOL BY MOTOKAWA (PRIVATE COMMUNICATION) SHOWING THE ROUTINE FOR DETERMINING ELECTRICAL THRESHOLDS. THRESHOLDS ARE INDICATED BY THE POSITION OF THE HORIZONTAL LINE NEAR THE BOTTOM OF EACH DATA COLUMN.

(See text for details)



ulus value for which judgments of "seen" and "not seen" have an equal probability of occurrence.

The method of limits is one in which the threshold is rather differently defined. As Guilford (9) has pointed out, much depends on the single terminal judgment of each series, at which the *S*'s

judgment shifts from "seen" to "not seen" or vice versa. The limits-comparison method of Motokawa has the advantage that it removes some of this emphasis on single judgments by providing that each series end only after the *S* has tried unsuccessfully to make several comparative judgments between the stimulus and a blank. There is still a considerable transition zone, however, within which this criterion of unsuccessful responses can be met; and the probability that it will be met at any time during a descending series increases as the stimulus intensity is reduced. It is also obvious that the *number* of unsuccessful responses is determined, at any point within the transition zone, by the total number of stimuli presented at that point. The use of gross steps entails the presentation of fewer stimuli within a given region, while finer steps increase the number presented. Therefore, in a descending method such as this, the threshold criterion of unsuccessful responses is most likely to be satisfied in a region of the transition zone in which fine steps are used.[15]

It is our contention that, in the determination of electrical thresholds, the probability of finding a threshold at a given point is increased by the use of fine steps in that region of stimulus intensities. Motokawa has realized this in his practice of using gross steps for "skipping over" the unwanted dark and apparent thresholds in his search for the true threshold. He has used fine steps systematically in the region where the true threshold is expected to be found. It is evident from the protocol in Table 12 that an elastic procedure has been used to select the size of step interval from one part of the session to another. In the limits stage of the determination, Motokawa's routine calls for presenting different steps of intensity for the "dark" series and the series with light. He has also varied these steps for the different delay times used within the "light" series. After comparing is begun, step intervals of 50, 100, or 200 ohms have been used arbitrarily from one time to another. We believe that the effect of this procedure is to heighten the probability that large values of enhancement will be shown for those particular series in which gross steps have been continued to relatively low intensity levels. A further effect is that of yielding the remarkable degree of consistency that the "dark" thresholds have shown in the Motokawa laboratory. We have never been able to achieve enhancement values conforming to such smooth functions as are shown in Motokawa's papers.

Further confirmation of the importance of step size is provided by an experiment conducted in Motokawa's laboratory. Through the kindness of Motokawa we have illustrated the results of one of his experiments in Table 13. In this special experiment the series of descending stimulus intensities has contained approximately equal log intervals. Again the first column lists the resistance values, in ohms, used to control the stimulus intensity. As in Table 12, ascending values of resistance correspond to descending values of stimulating voltage.

The results shown in Table 13 indicate that Motokawa, too, fails to find a specific crest time when equal log steps

[15] Guilford (9) has discussed a somewhat analogous situation in the determination of a difference limen. He says, "Having a preconceived notion that Weber's law holds, E will use smaller steps in the lower part of the scale and larger steps in the upper part of the scale. It is conceivable that, with a highly experienced O or E, unless measures are taken to prevent it, Weber's law or any other law could be demonstrated to hold merely by a systematic choice of steps."

TABLE 13

ADAPTATION OF A PROTOCOL BY MOTOKAWA (PRIVATE COMMUNICATION) SHOWING A SPECIAL EXPERIMENT IN WHICH EQUAL LOG STEPS WERE EMPLOYED

(See text for details)

	R_0	R_0	R_1	R_0	R_2	R_0
2000 -						
	o w	o	o	o	o	o
	o w	o	o	o	o	o
	o vs	o	o	o w	o	o
	o w	o	o	o w	o w	o
	o w	o	o	o. w	o	o
2500 -	o w	o w	o	o w	o w	o
	o com	o w	o	o	o w	o
	xox	o w	o	o	o w	o
	o	o com	?xo com	o	o	o
	o	o	o	o	o	o
3000 -						
	o	o	o	o	o	o w
	o	o	o	o com	o	o w
	o	xoo	o	o	o com	o w
	o	o	o	xoo	o	o vw
3500 -						
	o	o	o ?	o ?	xoo	o com
	o	o	xx	xx	xx	o
	o	o	x	o	x	o
4000 -						
	o	o	o	xx	x	o
	xox	xx	o	oo	x	oo
	x	x	xx	xx	x	xx
4500 -	x	x	x	x	x	x
	x	x	x	x	x	x
			x	x	x	x
5000 -						
			x		x	
			x		x	
5500 -			x		x	

of intensity are used. That is, thresholds obtained in the dark (R_0) condition are no higher than those following flashes of red light by one (R_1) or two (R_2) seconds. Consequently Motokawa concludes, and we agree, that no specific enhancement is revealed by red light with a one-second delay time under the conditions represented by Table 13. Motokawa has interpreted this to mean that the method of equal log steps involves too many presentations of electrical stimuli above the threshold, with a resulting long-term insensitivity to the very weak stimuli that lead to such low thresholds as that of R_1 in Table 12. He has supported this interpretation by citing his most recent experiments (personal communication) which show that repeated high-intensity electrical stimuli produce long-lasting elevations in electrical threshold.

Our own interpretation is simply that the crest-time phenomena appear only when higher levels are skipped over and

stimuli are massed, by the use of small steps, at the lower levels. No long-lasting changes in electrical threshold have appeared in our own experiments. Such effects are negated by the following considerations: *(a)* Polarization effects or other changes in skin-electrode resistance are minimized by our use of the 200,000-ohm resistance in series with the *S.* *(b)* The data of Experiment I do not reveal a rising trend with repeated stimulation. *(c)* In our control experiment, thresholds obtained with a 7.65-sec. cycle were not higher than thresholds obtained with a 15.3-sec. cycle.

The Achromatic Nature of Our Enhancement Effects

Such enhancement effects as we have been able to observe appear to originate not from the color response mechanisms but from the scotopic system of the eye. This was first apparent in the course of Experiments II, III, and IV in which small central fields of light were used. It was under precisely these conditions that Motokawa obtained his most clear-cut results on the relationship of the time-course of enhancement to the wave length of the stimulating light. Experiments V, VI, and VII showed that even more marked enhancement effects occurred when the field of light was extended to cover a wide retinal area. In this case the scotopic nature of the effect was even more readily apparent. It was concluded that in all of these cases the degree of enhancement was related to the extent to which the rod-receptor mechanisms of the eye were affected by the light.[10] It was assumed that stray light acting on peripheral receptors accounted for these effects under the small central area condition of stimulation.

It is our conviction that the specific wave-length effects that Motokawa has described are the result of his very special method of experimenting in which the protocol is modified in accordance with the responses of the *S.* We have been unwilling to depart from a rigidly defined protocol in our threshold determinations, fearing that any such departure might influence the results in favor of some preconceived hypothesis. We are ready to admit that our negative results with regard to specific wave-length effects may simply mean that these effects are so subtle that they are masked by the ordinary variability of our threshold determinations. If this is so, however, we can hardly endorse the use of this method for studying the basic characteristics of color vision.

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[10] Consistent with this view is the fact that the phosphenes themselves appear colorless; this suggests that the electrical current does not affect the color response mechanisms when intensities of stimulation are low. It is likewise true that *Ss* typically report that the phosphenes appear in the periphery of the visual field, where relatively few color receptors are found.

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